Reducing the Impacts of Agriculture on Air Quality

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The previous chapters discussed how the levels and types of gaseous[1] and particulate emissions could vary in the agricultural sector according to practices, animal and plant species, livestock conditions and related factors (buildings, storage, grazing and spreading), as well as soil and climate conditions for crop management. They also explained the processes behind these emissions and highlighted the main factors influencing these processes. The purpose of this chapter is to show how researchers, agricultural stakeholders and policymakers can use this knowledge to identify measures to reduce these emissions at different organization levels.

[1] Since agriculture is not considered a sector that contributes significantly to non-methane volatile organic compound (NMVOC) emissions in France, it is not a targeted area to reduce these types of emissions. Knowledge about these compounds is also not the same as that of other compounds; for both these reasons, specific practices for mitigating these emissions have not yet been identified. As such, NMVOCs will not be discussed in this chapter.

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Emission control must be part of crop and livestock management and, more generally, of farming system operations, from both a technical and an economic point of view. Emissions from agriculture-related air pollutants are of course relevant to the agricultural system itself, since they often point to inefficiencies (e.g. nutrient loss with ammonia volatilization). But they also affect the relationship between agriculture and society, given that they contribute to the degradation of air quality and the many associated health and environmental impacts. These relationships cover a range of spatial scales, from the community level to air pollution regulation at regional, national and continental levels.

Emission mitigation measures must therefore consider multiple factors, from natural to human and regulatory. This chapter aims to show the complexity of moving from process analysis to action by covering some (but not all) possible initiatives, from the most local to the broadest scale.

1 Individual Practices at Farm Level

Due to the variety and heterogeneity of sources and the mostly diffuse nature of agricultural emissions, there are multiple levers for mitigating emissions in this sector, each relatively specific to the stages and compounds. The choice was made not to present in detail all the techniques that can be mobilized and recognized as effective. These are detailed in various reports, namely: a good livestock farming practices guidebook,[2] published by the French Joint Technology Network, Livestock production and Environment (Guingand et al. 2019); an analysis carried out on behalf of ADEME on the potential of ten actions to reduce ammonia emissions from French livestock farms (Martin and Mathias 2013); the Guidance document on preventing and abating ammonia emissions from agricultural sources, published by the Executive Body for the Convention on Long-range Transboundary Air Pollution

[2] *Guide des bonnes pratiques environnementales d'élevage* (Available at http://www.rmtelevage-senvironnement.org/nouveau_gbpee_2019, in French only)

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(Sutton et al. 2015); the Best Available Techniques (BAT) References Document for the Intensive Rearing of Poultry or Pigs (Santonja et al. 2017); and the Guide to good agricultural practices for improving air quality (CITEPA 2019), recently published following the French National Air Pollutant Emission Reduction Plan (PREPA) for the adoption of mitigation practices by farmers. Since most of the principles underlying the mitigation techniques are based on common physical, chemical and biological processes, the choice was made to present practices by the type of effect mobilized. The very first level of classification reflects the fact that it is possible to influence both the level of the activity itself and the emission factor/rate of the activity in question (see chapter "Establishing a Diagnosis: Inventorying, Monitoring and Assessing", "Inventories").

1.1 Mitigating Agricultural Activity

For crops and grasslands, emissions are linked to the total areas dedicated to these types of production, as well as to the quantities of inputs used per unit area. For livestock production, they primarily depend on the number of animals and the characteristics of the manure. Three types of actions are possible to modulate the level of agricultural activity.

1.1.1 Reducing the Scope of Activity

The most direct type of action is to reduce the number of livestock, but this would lead to a decrease in production and a risk of no longer being able to meet consumer demand. The only way to balance these needs would be to increase imports of animal products or reduce the amount of animal protein in human diets (this takes time to be effective). For crops, it means converting cultivated land to other types of land use. In addition to questions about the future use of these converted areas and the resulting income losses for farmers, there is also the risk of no longer meeting the world's food and feed needs or other biomass needs for energy and chemistry.

1.1.2 Increasing Activity Efficiency

The second type of action consists in increasing the efficiency of the activity with regard to the inputs, i.e. finding ways to maintain the same level of production with less input.

In the case of cultivated areas, one way to do this is to optimize crop protection or control fertilizer application as precisely as possible: farmers can optimize the nitrogen doses and the dates of application to be as close as possible to the needs of the crops, or even accept slight deficiencies. The anticipated nitrogen balance method (Comifer 2013) is often applied by measuring the nitrogen balance at the end of winter or using decision support tools during the crop growing season (MAAF 2016). Plants take up nitrogen quickly because the nutrient is a limiting growth factor. This avoids excess nitrogen in the soil and therefore limits nitrogen losses in the environment. Similarly, intercropping can also help to fix soil nitrogen after harvest and reduce losses.

In the case of livestock production, feed efficiency must be improved, which leads to a reduction in the ratio between excreted and ingested nitrogen. This increase in nitrogen efficiency is applicable to all types of livestock: specific strategies to lower feed protein levels help reduce excreted nitrogen (particularly as urea in urine) without altering animal production performance. For cattle, the strategy is to reduce the overall protein ration. However, this ration is difficult to manage, especially for cattle farms with animals of different ages and therefore with different needs. This strategy may be risky for farm production and is therefore not widespread. Reducing the proportion of total nitrogen (TN) in the ration from 20% to 15% decreases the nitrogen excreted in urine by about 66% (Castillo et al. 2000). Adjusting the ration to the physiological stage and growth level of the animal would improve efficiency. Mastering animal feeding is even more challenging on pasture, where it is difficult to control the amount of ingested grass, which is often rich in nitrogen. For pig farms, the strategy entails adjusting rations to needs, which vary according to the animals' growth stages, in order to limit waste. A two-phase strategy that includes a "growth" feed with 16% TN followed by a "finishing" feed with 15% TN instead of a standard diet on a single feed with 17.5% TN reduces nitrogen excretion and ammonia (NH_3) volatilization in the building by 18% (Dourmad et al. 2016). This strategy is well established in France and feeding makes it possible to achieve even better results, thanks to successively using feeds with decreasing protein contents, adapted to the decreasing needs of animals. Lagadec et al. (2016) report an additional 40% reduction in ammonia emissions. For poultry farms, multiphase feeding is the benchmark, but can be further enhanced by increasing the number of phases. Another way to improve the efficiency of ingested nitrogen consists in altering the availability of proteins and changing the balance between amino acids, either by using specific raw materials or by supplementing with synthetic amino acids. Nitrogen excretion in poultry can thus be reduced by 10% for each 1% reduction of protein in feed.

This makes feeding a particularly interesting lever: it has proven to be effective with regard to all nitrogen compounds, regardless of their effects on the environment (mainly NH_3, but also NO_x, N_2O, and NO_3^-), as well as where manure is managed (buildings, storage areas, field application). Of course, this excludes grazing, but this is the least-emitting stage. Moreover, this strategy to reduce emissions at the source does not involve major investments (compared to building improvements, for example) and can even save farmers money since it requires fewer nitrogen inputs.

1.1.3 Adopting Alternative Practices

The third type of action consists in adopting practices that cause fewer emissions. Because alternative practices are more extensive, adopting them is one part of a general framework for changing the technical, economic and social management of the farming system.

A significant reduction in the amount of nitrogen excreted by animals at the building (one of the highest emitting stages) can be achieved by increasing the time animals spend at pasture when soil and weather conditions allow. Nitrogen emitted on pasture is less prone to emissions (due to infiltration of urine into the soil, recovery of ammonia by vegetation, etc.) than across the "building-storage-spreading" chain (Pellerin et al. 2013). Achieving this often requires increasing the proportion of grassland areas and reorganizing farm work. However, this extended grazing period may, depending on the agropedoclimatic conditions of the farm, increase the risk of nitrate leaching, and therefore simply move pollution from the atmosphere compartment to the water compartment. These effects should be analysed, along with other issues, before implementing such a change.

One alternative to using synthetic nitrogen is the introduction of legumes either in the rotation (which generally requires longer rotations), or in association with traditional crops or within grasslands (ADEME 2015). Bacteria living in symbiosis with leguminous plants naturally fix atmospheric nitrogen (Chapter "Mechanisms of Pollutant Exchange at Soil-Vegetation-Atmosphere Interfaces and Atmospheric Fate"), limiting the use of fertilizers that cause nitrogen surpluses that are favourable to emissions. However, attention must be paid to crop residue management, which is often nitrogen-rich when multi-year crops are incorporated.

Ammonia volatilization can also be reduced by using a fertilizer with low volatilization potential (e.g. ammonium nitrate) instead of fertilizers with a high volatilization potential (e.g. nitrogen solution, or urea in granular form, which has an even higher potential). This difference between fertilizers is due to the proportion of nitrogen in urea or ammonia form (100% for urea, 75% for nitrogen solution, 50% for ammonium nitrate) and the ability of this nitrogen to volatilize. Moreover, urea hydrolysis leads to alkalinization of the environment and thus to higher emissions than in a more acidic environment (Chapters "Mechanisms of Pollutant Exchange at Soil-Vegetation-Atmosphere Interfaces and Atmospheric Fate" and "Establishing a Diagnosis: Inventorying, Monitoring and Assessing"). However, this substitution may require adapting the spreading equipment as well as the supply of synthetic fertilizers.

Alternatives to pesticide use are also being studied, as summarized in Charbonnier et al. (2015), which present the results of research projects carried out under the Pesticides Programme of the French Ministry for the Environment since 1999. These alternatives cover different types of solutions, including biological vector control, physical control (e.g. nets for protecting orchards, etc.) or changing agricultural systems.

1.2 Reducing the Emission Factor

1.2.1 Reducing Surface Area and Contact Time with the Atmosphere

Emissions are partly determined by the surface area and the contact time between the input product and the atmosphere. Thus, any practice that reduces either or both is likely to abate emissions for all compounds, including N compounds, pesticides and BVOCs. The interest of implementing such practices, in addition to reducing pollutant emissions in the atmosphere and therefore their impacts, is coupled with the reduction of odours (from livestock manure management) and the recycling of other N-containing organic amendments applied to agricultural lands.

In animal buildings, the areas where manure accumulates (the building itself, particularly for cattle and poultry; pits for pig, cattle and duck manure) represent larger areas than those of outdoor storage. The idea is therefore to evacuate manure from livestock buildings to storage areas more frequently and efficiently, regardless of the type of evacuation (gravity evacuation, scraping several times a day, flushing with water). For example, Guingand (2000) showed that evacuating manure from a pork farm every 15 days reduced ammonia emissions by nearly 20% compared to evacuating only at the end of the batch. For floor scraping inside buildings to be effective, farmers must shift from one or two scrapings to six or eight per day. For farms with laying hens in cages, a very significant reduction in building ammonia emissions (ranging from 50% to 80%) has been achieved by implementing rapid faecal disposal by means of collection and disposal belts. However, if scraping is not carried out efficiently (e.g. if the ground is too rough, or because straw is used), increasing the scraping frequency can lead to the opposite effect. This may be one of the reasons why scraping does not always appear to be effective in cattle farming. These more frequent evacuations reduce the storage time of manure in livestock buildings, and therefore the contact with air over relatively large areas, but lead to an increase in storage times and volumes outside the building, which must be controlled as well as possible.

For outdoor storage, the most effective way to reduce emissions is to cover the storage area. More specifically, this is implemented for slurry management and is particularly effective at controlling ammonia emissions, as well as other nitrogen compounds and methane. Covers may be natural, with manure forming a crust on the surface when the pits are not stirred, especially if the animals have been raised with the use of litter: this physical barrier to emissions reduces methane and ammonia emissions (by about 40%), whereas it increases N_2O emissions, compared to stored manure without a crust. Using artificial covers (such as fixed covers or floating covers of various materials) reduces ammonia emissions by 60% to 80% depending on the source. It also limits the dilution of effluents by rainwater as well as odour emission. Additionally, manure or digestate storage tanks are now increasingly transformed into biogas production digesters to produce energy.

The techniques used to reduce the time and duration of contact between the compound and the atmosphere are most commonly used for field application of either organic or inorganic fertilizers, and they are among the most effective. For organic fertilizers, all products are considered on the same level, regardless of origin: livestock (solid, liquid and slurry manure, animal compost), residential areas (sewage sludge, municipal waste compost, green waste compost) and agro-industries (vinasse from alfalfa dehydration plants, sludge, sugar plant waste water).

One technique consists in incorporating the substrates directly into the soil. Liquid products are injected at various depths. This practice is also being developed for mineral fertilizers, particularly before the establishment of spring crops, with localized supply for fertilizer granules. In both cases, this technique is very effective for ammonia, reducing emissions to only a few percent of what they would normally be with a conventional surface application. In current practice, reported reductions are around 70–90% for manure (Langevin et al. 2015); the effectiveness of the technique depends on the quality of the furrow injection closure. N_2O emissions may not be impacted, but when injection is carried out on very wet soils, they can be significantly increased (Chapter "Mechanisms of Pollutant Exchange at Soil-Vegetation-Atmosphere Interfaces and Atmospheric Fate").

Another solution is to reduce the overall surface area of liquid manure by application in narrow bands, using the trailing hose or trailing shoe technique: about one-third of the area is covered by the product, and the reduction in NH_3 emissions averages 30–60% (Langevin et al. 2015) compared to standard surface broadcast applications. If application is carried out in the presence of a plant canopy, the reduction can be as much as 80%, when microclimatic effects and stomatal absorption are included.

Finally, when deep injection is not feasible, as in the case of many pesticides, solid manure or certain soil conditions (too stony or too steep), incorporation by soil tillage after application is an efficient way to reduce emissions. This practice is especially relevant for compounds whose emissions result from purely physicochemical processes, such as ammonia and pesticides. Its effectiveness increases (volatilization reduced by up to two orders of magnitude) when the time between application and incorporation is short (Bedos et al. 2006; Langevin et al. 2015), as well as when the incorporation is deeper, which depends on the tool used (e.g. plough or tiller at 25 cm, incorporation at between 5 cm and 15 cm with disc or tine cultivators for organic fertilizers, or at 2 cm to 3 cm for mineral fertilizers) (Smith et al. 2009) and the soil and meteorological conditions are best adapted.

Another way to reduce NH_3 emissions is to fertilize shortly before rain or to irrigate after application: in this case, not only is the compound carried deeper into the soil, but it is also diluted in the soil solution, leading to lower surface concentrations and lower emissions. Emissions reduction is most effective when the rainfall or irrigation rate and intensity are high, and the time between application and irrigation or rain is short (Smith et al. 2009). However, this increases the risk of leaching and runoff contamination of surface water.

A number of solutions can reduce the transfer time between the spraying nozzles and the target during pesticide application. For example, the use of anti-drift nozzles or a reduction in the height of the spray booms reduces both drift and the possible volatilization of the active ingredient (Textbox 1). It should also be noted that, in order to limit the atmospheric transfer of dust from the seed treatment coating generated by abrasion, deflectors have been added to seed drills.

Textbox Effectiveness of methods for limiting pesticide emissions by drift

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When measuring pesticide drift in the field, one immediate challenge is the level of imprecision in terms of sampling time and spatial sampling strategy. Accordingly, measurement protocols were developed according to the practical needs for risk management based on two main principles. Historically, potential contamination of surface waters was assessed by estimating deposits on a horizontal interception plane with a given distance downwind. Recent concerns about air contamination have brought about a more appropriate protocol that considers a vertical interception plane at the edge of the treated field. While the ISO 22866 standard provides this protocol for the interception of liquid particles using passive sensors (polytetrafluoroethylene (PTFE) thread type, 2 mm diameter), studies have shown larger quantities being collected with active samplers in isokinetic conditions.

At European level, agri-environmental measures aiming to limit the risk of drift have been introduced in the product's marketing authorization process. They generally combine structural measures (minimum distance from targets for applications), the use of equipment that reduces drift, and specific application practices. The first level corresponds to untreated buffer zones. Use of these buffer zones was adopted in 2006 in France; they must be five metres wide along permanent watercourses and be a structural measure for agricultural field management at landscape scale. These buffer zones are generally grassy or riparian strips that reduce the risk of surface water contamination by approximately two-thirds according to risk management models for water conservation. Untreated buffer zones are specified for the protection of adjacent non-target plants and crops as well as arthropods. Finally, the use of windbreaks, hail protection or insect-proof nets in fruit production is considered to provide an equivalent risk limitation in some European countries. Buffer zones for areas near schools or hospitals, for example, are regulated in France at the local level by prefectoral decrees. Discussions are ongoing about extending such protections to all residential areas. The second level of management measures involves the obligation of using equipment such as drift reducing nozzles, tunnel sprayers etc., which also confer a two-thirds reduction in risk compared to a baseline situation. The use of this equipment is mandatory when applying any product with an untreated buffer zone greater than five metres and which is applied up to five meters along water streams. In France, a list of approved equipment is published periodically in the Official Bulletin of the French Ministry of Agriculture. In other European countries, the level of risk limitation for the equipment can vary from 50% to 95%. Finally, the third level of management measures corresponds to the systematic application of best application practices, in particular with regard to reduced air assistance along field edges, lower driving speeds or the reduced ramp heights.

1.2.2 Reducing Concentrations

Gaseous phase concentrations at the interface between the source and the atmosphere are a strong driver of emissions. There are several effective solutions to limit surface concentrations: by dilution as mentioned above, by trapping the compound, by shifting the physical or physicochemical equilibria to other less volatile forms, by slowing down biological reactions producing the compound, or by promoting other reactions that consume the compound in question or its precursors.

In cattle farming, one practice aims to modify the reaction sequence leading to the production of enteric methane in order to switch to less polluting chemical species: the feeding strategy consists in replacing a portion of the carbohydrates in the ration with lipids. Carbohydrates produce hydrogen, and therefore methane, but fats do not. The reduction is effective and sustainable, and is reinforced by the negative action of lipids on rumen protozoa (Doreau and Ferlay, 1995): a 4% reduction per point of lipids substituted for carbohydrates was observed (Doreau et al. 2011). The same effect is obtained by adding additives, such as calcium nitrate, either alone or in combination with lipids (Lee and Beauchemin, 2014): the nitrate in the ration is transformed into nitrite and then into ammonia in the rumen, which consumes hydrogen.

In pig farming, misting can be carried out for capturing ammonia and dust inside the building by installing ramps with nozzles, particularly during particle production phases such as laying bedding, cleaning or collection. Dust and ammonia concentrations inside the building are reduced, as well as transfer to the outside. A reduction efficiency of 14–46% for particulate matter and 22–30% for NH_3 emissions was achieved for pig buildings. Similarly, to limit the extraction of ammonia and particles produced in livestock buildings, air scrubber systems can be installed at the air outlets if the building design allows: this may be possible in pig and poultry farming, but rarely in cattle farming, where buildings are generally naturally ventilated. Air washing reduces NH_3 emissions in pig houses by 40–90%. Washing is even more efficient when water is replaced by an acidified solution that more effectively traps alkaline compounds such as ammonia: the reduction achieved is 70–90% for ammonia emissions in both types of livestock, and for particulates, 60–80% in pig houses and about 35% in poultry houses.

Another very effective strategy in controlling, or rather changing, a share of the emissions released into the atmosphere is a matter of upstream structural choices. This strategy can also consist in controlling certain aspects of the environmental conditions of the livestock and storage methods. Indeed, depending on the management methods (namely type of floors in the building and whether or not litter is used) and the environmental conditions (temperature, humidity in particular), some reactions or equilibria are favoured and others not. For example, in pig farming, ammonia emissions may be lower on well-managed bedding than in slatted flooring, and N_2O (and N_2) emissions higher (Corpen 2003), while the opposite is observed in wet bedding (Dourmad et al. 2016). Similarly, the increase in bedding material in straw-housed pig farming favours the immobilization of ammoniacal nitrogen by microorganisms, reducing NH_3 availability. It should be noted that straw can act as a barrier between urine and air, which also limits volatilization. For poultry, ammonia emissions are reduced by maintaining a low moisture content in the litter, either by adding carbonaceous substrates, by installing anti-leakage and anti-waste watering systems (reduction of 20–30%), or by setting up a system to accelerate litter drying (reduction of 40–60%). Doing so also reduces methane emissions. In cage-based poultry farming where rapid evacuation of faeces is practised, as is generally the case in France, the addition of a system for pre-drying the harvested faeces in the building allows a further reduction of 30–40%. The action continues during storage, where rapid drying can be achieved in an outdoor drying system if the droppings are spread in thin layers and ventilated.

Effluent phase separation, which is even more effective at reducing emissions of ammonia and other nitrogen compounds when performed early, refers to the same type of action: the separation of urine and faeces makes it possible to limit the hydrolysis of urea from urine and thus the production of mineral nitrogen, and especially ammonia. Indeed, urease, the enzyme responsible for this degradation, is produced in faeces. Thus, if the slurry emptying described above is connected to phase separation, efficiency increases: this is the case with certain types of scrapers, such as serrated belts with scraping straps, or certain types of floors, such as floors with a slight transverse slope and a central gutter for liquid recovery. In the latter case, ammonia emission reductions of 40% in pig farming have been measured. One pig farming storage practice consists in treating slurry using the biological process of nitrification-denitrification: some of the ammoniacal nitrogen is thus converted into atmospheric nitrogen N_2 (Chapter "Mechanisms of Pollutant Exchange at Soil-Vegetation-Atmosphere Interfaces and Atmospheric Fate"), allowing a reduction in emissions both during storage (up to 70%) and spreading.

Shifting equilibria towards non-volatile forms is specific to ammonia: under acidic conditions, the dissociation equilibrium between the ammonium ion and ammonia in aqueous solution is shifted to the non-volatile ammonium form. In laying poultry farming, the pH decrease is achieved by adding calcium sulphate to the feed: at a rate of 6.9%, it results in a 39% reduction in ammonia emissions and a 17% reduction in methane emissions (Wu-Haan et al. 2007). In pig farming, urine acidification is carried out during the growth or finishing phase by incorporating benzoic acid ($C_7H_6O_2$) into the feed: at a rate of 1%, a maximum 20% reduction in NH_3 emissions can be achieved at the building. Another practice, used only in northern Europe (e.g. Denmark, Germany), is to acidify the slurry very significantly (to pH 4 or 5) by adding sulphuric acid at the various stages, in the building and during storage and spreading. If the pH is kept below 6, it can lead to a 60% reduction in NH_3 emissions during storage. However, if acidification is practised in buildings, due to its high buffering capacity, the manure discharged and stored in an external tank has a pH around 7, and the reduction does not reach the expected levels afterwards.

1.3 Adopting an Integrated Multistage and Multicomponent Approach

A number of actions are already being undertaken by the livestock and crop sectors to implement the available technical solutions in the field. However, they do not all have the same reduction potential and, because they were developed to mitigate emissions of a compound at a specific stage, their effectiveness is generally assessed at the scale of the compound and stage in question.

However, there are strong interdependencies between different stages on the same farm, and the implementation of a practice to reduce emissions at one stage can lead to an increase in emissions at another. Emission control is particularly complex for livestock production systems, as it must address all stages of effluent management (buildings, storage, spreading, grazing). The effectiveness of one good practice at farm level can be reduced by the absence of good practices at downstream stages. Ammonia is an illustrative example: covering slurry pits conserves nitrogen, but produces a slurry richer in ammoniacal nitrogen and thus with a higher potential for volatilization when applied to the field. This underscores the importance of this last stage. The combination of strategies, techniques and/or conduct aiming to reduce gaseous emissions must therefore be considered at the scale of effluent management as a whole.

There are also strong interdependencies between the processes that emit these compounds and processes involving other compounds. Levers used to reduce certain emissions can modify the biological and physicochemical processes that cause emissions of other chemical forms in other environmental compartments (water, soil) in a positive or negative way. This phenomenon refers to pollution transfer with impact transfer. These pollution transfers can be observed within the cycle of the same element. For example, with nitrogen, techniques for reducing ammonia emissions in the field can increase nitrous oxide emissions, and therefore can impact global warming; nitrate leaching can also be promoted, with negative consequences on water quality. These pollution transfers can be even more complex: for instance, reduced tillage includes a set of practices that reduce particulate emissions in the field; but because these practices can cause weed control problems, farmers may end up using more pesticides.

Fortunately, in some cases levers mobilized for one stage and one compound are effective for another stage and/or another compound. For example, the strategies implemented to reduce ammonia emissions from buildings and storage have often been shown to be equally effective for methane. Others make it possible to reduce emissions of all nitrogen compounds at several stages or even across all stages. Thus the entire chain must be considered to avoid pollution transfers between stages and between media (water, air, soil) and effectively limit emissions. This means that assessing the environmental performance of mitigation practices must be carried out in an integrated manner (in terms of scale and evaluation criteria) (Espagnol et al. 2015). For this assessment to be complete, observations must be made in the field and be repeated in order to monitor possible changes in performance over time.

Furthermore, it is important to note that emission mitigation strategies are part of overall farm management, which takes into account organizational, economic and social criteria. As a source of air pollution, ammonia volatilization also reflects a loss in fertilization efficiency for farmers, whereas improving nitrogen management can enhance production. In general, optimizing input use (fertilizers, pesticides, energy, animal feed) helps reduce overall losses to the environment, while also limiting the vulnerability of farms to price changes. Levers have long been established to reduce ammonia and particulate emissions from livestock buildings; the aim is not so much to improve outdoor air quality, but rather to improve indoor air quality and animal welfare.

2 Levers for Action at Higher Levels of Integration

The previous section described how measures at the plot and farm level essentially aim to reduce pollutant emissions. Chapter "Necessary Integrative Approaches" demonstrated that it is useful – even essential – to consider basic processes and actions in relation to the pollutant cycle within a broader context. Indeed, depending on the characteristics of the area, emissions can be captured by neighbouring natural, forest or agricultural ecosystems, and thus reduce the net quantities contaminating the atmosphere. This depends mainly on the landscape arrangement and the organization of agricultural operations at farm level. The deposition of pollutants on neighbouring ecosystems is likely to have an even greater impact if these ecosystems are sensitive to these inputs. Additionally, rural areas have many different natural ecosystems and agroecosystems that do not all emit pollutants at the same time. While excess concentrations can be observed occasionally on a plot (e.g. after the application of fertilizers), their dilution in a landscape where less emitting areas coexist generally reduces their potential impact.

2.1 Consider the Environment of Agricultural Activities

Due to their well-developed aerial surface and the affinity of vegetation for certain pollutants, vegetation near a source can recover significant amounts of pollutants, thereby removing them from the atmosphere (Loubet et al. 2009). This recapture is even more effective when the canopy has a high vertical development (forests, hedgerows) and a well-developed aerial surface, and so a high leaf area index. This effect is increased by the position of agricultural sources near the surface: at soil and vegetation surface level for mineral or organic fertilizer applications, to one to a few metres from the ground for pesticide applications or livestock building exhaust air.

2.1.1 Recover Pollutants by Developing the Area Around an Agricultural Source

Loubet et al. (2001, 2009) showed that a tree belt around a livestock building could capture up to 10% of the ammonia emitted by it. More recently, Bealey et al. (2014) estimated that this figure could be reach up to 20% for a livestock building and 45% for livestock farming in wooded areas. The captured portion mainly varies based on micrometeorological conditions, including wind speed and atmospheric stability, and according to the vertical development of the tree belt, its width and the level of nitrogen nutrition of the trees (a high compensation point, corresponding to high internal ammonium concentrations, limits capture). Figure 1 from Fowler et al. (1998) shows that deposition and concentrations are high (15 m) near a poultry building, but fall rapidly with distance (they decrease by a factor of ten at 270 m from the building). This study also illustrated the magnitude of deposits, which reach several tens of kg $NH_3 \cdot ha^{-1} \cdot year^{-1}$ along the tree belt. Modelling work estimated that the tree belt recovered just over 3% of the ammonia emitted by the building. This recovery is significant, but it can be limited by saturation effects: because the trees closest to the building receive large deposits, their compensation point can become high and their cuticle saturated with ammonia, with a high pH, unfavourable to deposition. Bealey et al. (2016) assessed the effect of local planning on national reactive nitrogen budgets in Great Britain. Planting trees around about 20% of intensive farm houses would reduce national emissions and subsequent wet deposition by about 2%, and reduce emissions leaving the country by the same amount.

This type of spatial planning is therefore effective in recovering and protecting sensitive ecosystems (Hicks et al. 2011) near agricultural activities or livestock buildings. However, these deposits cause impacts on the tree belt itself. Pitcairn et al. (1998) were thus able to show an effect on biodiversity within the tree belt,

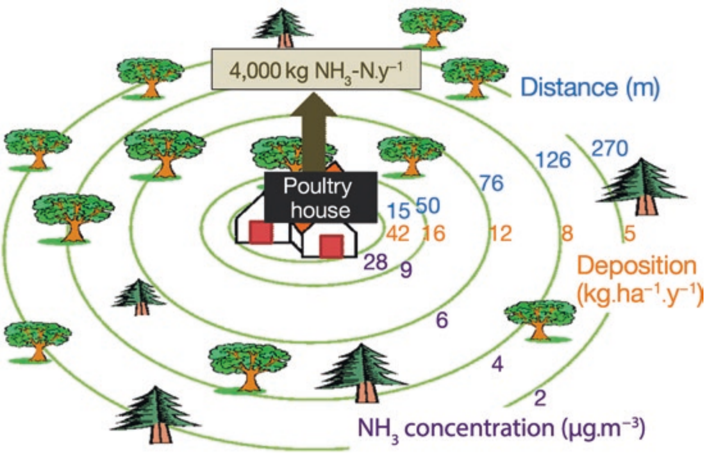

Fig. 1 Spatial variations in ammonia concentrations and ammonia deposition within a 270 m radius around an industrial poultry house. (Based on Fowler et al. 1998)

Table 1 Studies on the effectiveness of windbreaks in reducing pesticide drift

Study	Type of crop	Type of windbreak	Decrease in drift	Country
Lazzaro et al. (2008)	Not specified	Plane trees and other hardwoods	Reduction over the first 12 metres downstream of the hedge: > 80%.	Italy
		Height: 7–8 m		
Wenneker et al. (2005)	Apple trees	Alders, coniferous and willows	Reduction over the first 8 meters:	Netherlands
		Height: 4–5 m	−10%–20% (no foliage)	
			−60%–85% (full foliage)	
Richardson et al. (2004)	Apple trees	Corn alders and white alders	Reduction over the first 3 metres:	Great Britain
		Height: 5–6 m	−50% (still developing foliage)	
			−80% (full foliage)	

Based on Vézina and Talbot (2011)

with nitrophilous species becoming denser near the building to the detriment of other species. In addition, this type of planning takes a significant amount of space, since these belts must extend over dozens of metres to be effective. But they can provide other environmental services: landscape amenity, noise and odour mitigation, and wildlife habitats.

Numerous micrometeorological analyses show that hedgerows or windbreaks are also effective in intercepting windborne particles (Bouvet et al. 2007; Raupach et al. 2001). This effect can be used to limit the drift of pesticide spray droplets beyond the plot where they have been applied. Planting windbreaks in orchards can therefore contribute to a significant decrease in pesticide drift (Table 1): a windbreak in full foliage maximizes pesticide interception (60%–85%) compared to a hedgerow without or with still developing foliage (10%–50%).

Such natural structures should also be effective in limiting the transfer resulting from the volatilization of pesticides from the soil or plant in the same way as for ammonia. The initial assessments were carried out mainly by modelling, and should be rounded out by including additional processes in models such as the deposition of compounds on the hedgerow, for example, and by the acquisition of experimental datasets (Bedos et al. 2016).

2.1.2 Modify the Landscape Mosaic to Maximize Local Pollutant Recapture

Since pollutant capture by neighbouring ecosystems is greatest at transitions between ecosystems, recapture is expected to be greater in fragmented landscapes where interface lines between plots are more present and source and sink areas are closely interconnected. This can be shown by modelling, but it is not possible to demonstrate it experimentally beyond an elementary landscape pattern (e.g. from upstream to downstream of a hedge). Re-planning agricultural landscapes for this reason alone seems irrelevant, but it should be stressed that this solution is in many ways in line with the possibilities of shifting agriculture towards crop diversification or re-associating livestock and cropping, which all lead to a stronger mix between sources and sinks. It is therefore another strong argument for moving towards multifunctional landscapes.

2.1.3 Changing the Location of Sources to Protect Sensitive Ecosystems

As discussed in chapter "Mechanisms of Pollutant Exchange at Soil-Vegetation-Atmosphere Interfaces and Atmospheric Fate", dry pollutant deposition is largely determined by the concentration of the pollutant in the air at the sensitive ecosystem level (Bobbink and Hettelingh 2011; Hicks et al. 2011). As explained above, landscape structures such as tree belts can reduce concentrations over a sensitive area by capturing some of the pollutants emitted and increasing atmospheric turbulence, thereby lowering concentrations near the ground downstream of the tree area. But the main factor that reduces concentrations is the distance from the source to the sensitive area. The idea here is to position potentially large sources such as livestock buildings containing a large number of animals so as to respect critical levels for the ecosystems affected. For example, Dragosits et al. (2006) modelled the effect that could result from moving an "industrial" poultry house farther away from a protected natural area. Figure 2 shows the effectiveness of such an option, which reduces deposition in the protected area by up to 100 kg N·ha^{-1}·year^{-1}.

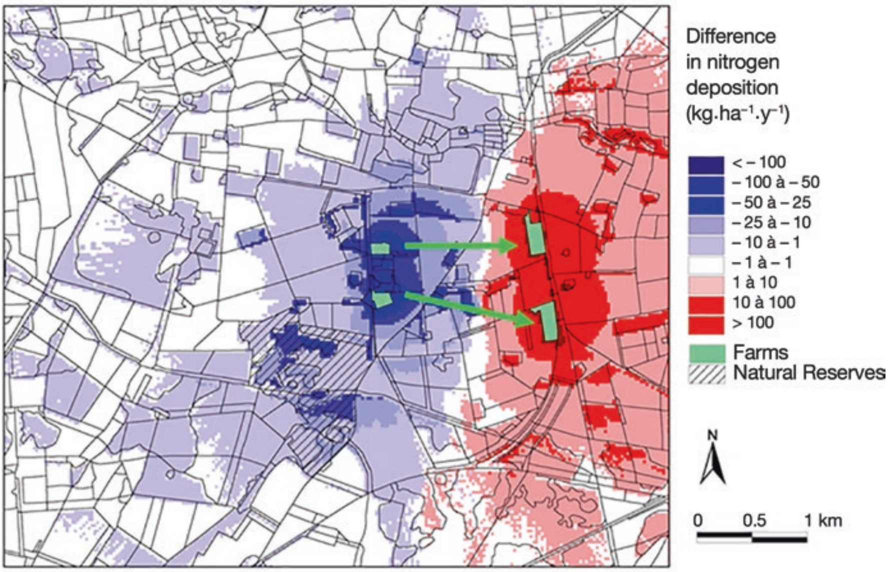

Fig. 2 Change in dry ammonia deposition calculated by moving a poultry house located near a protected natural area (hatched area) farther away (about 1.5 km eastward). (Source: Centre of Ecology and Hydrology, Edinburgh, UK; based on Dragosits et al. 2006)

2.2 Reduce Emission Peaks at the Regional Level

Health and ecotoxicological risks in terms of air pollution are related to the concentrations of pollutants in the atmosphere. Indeed, at low pollutant concentrations, organisms generally have the ability to metabolize pollutants or activate detoxification mechanisms. An effective way to limit impacts is therefore to distribute emissions as effectively as possible over time and space to avoid large concentrations.

As such, grouping similar production systems in certain regions can be extremely detrimental. Two examples in France are especially illustrative of this: first, the concentration of livestock activities in western France since the second half of the twentieth century, and second, the country's vineyard areas, which are grouped in different designated areas. In the first case, agroecosystems near livestock facilities do not have the capacity to absorb high ammonia emissions, whereas absorption would be more efficient if emissions were more moderate. However, the reason these activities are so concentrated is due to decisions taken that were independent of air quality considerations. These decisions related to regional development and economic efficiency of livestock sectors in certain regions, and vineyard designations of origin. In both cases, an underlying logic overlaps with the climatic potential of these productions. Although this is undoubtedly a rather distant consideration today, it can be pointed out that the criteria related to air pollution are in line with the issues under discussion on the deconcentration of agricultural activities, the links between agriculture and livestock farming and the diversification of production at the regional level.

Similarly, a better distribution of inputs over the annual cycle would often reduce the magnitude of emission peaks. Such an assessment was conducted in Denmark (Hertel et al. 2006). Figure 3, produced from this work, shows that banning autumn manure application to limit nitrate leaching in the winter resulted in delaying application in the spring, with the amount of manure produced annually remaining approximately the same for both years.

2.3 Case-by-Case Solutions in a Broader Context

For all these methods that integrate spatial planning, the actors must deal with complex landscapes for which they must take into account not only the system by itself (hedgerows, tree belts), but also the whole surrounding landscape. This requires considering interactions between the production system and its natural and man-made environment, with a long-term perspective. Solutions must therefore be determined on a case-by-case basis using relevant analytical tools. The issues raised by air quality on their own do not necessarily justify new measures, but in many respects such measures are right in line with developments to make agriculture more environmentally friendly.

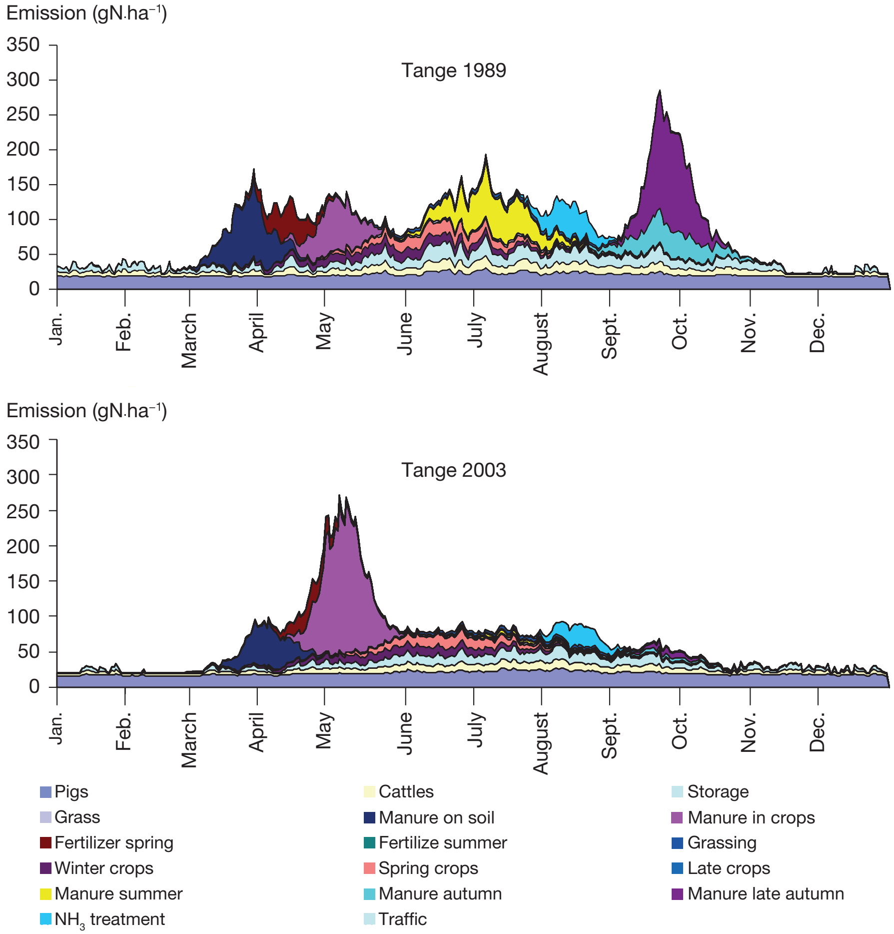

Fig. 3 Seasonal variations in ammonia emissions modelled in Tange (near Aarhus) in Denmark in 1989 and 2003. The difference between the 2 years results from a change in legislation on the spreading of livestock manure. (Based on Hertel et al. 2006)

3 Multiple Perspectives from Agricultural Actors and Civil Society on Agriculture and Air Quality

As agriculture underwent major changes in the mid-twentieth century, society viewed agricultural actors positively thanks to new technological developments in the sector and a moral contract with society to provide food. In their article entitled "The fifty years that changed French agriculture", Bourgeois and Demotes-Mainard (2000) noted that "while the number of agricultural workers has been divided by five in fifty years, agricultural production has more than doubled in volume. As a result, productivity per person has increased more than tenfold. Agricultural production has increased twice as fast for plants as compared to animals". But from the end of the twentieth century, urban societies' views shifted. Many key agricultural activities began to be seen by part of society as harmful to the environment: certain types of livestock were removed from the land, less attention was paid to soil quality, and farmers began using more synthetic products (fertilizers, pesticides, veterinary products). Today, some practices are considered a threat to health and food quality, on par with industrial activities. There is a growing interest in production systems considered more virtuous because they use fewer inputs, or which are simply closer to consumers, with more visible actors, as well as in dietary changes (e.g. community supported agriculture, organic farming, eating less meat, buying locally produced products). These systems generally result in fewer pesticides in the atmosphere because they use limited (or no) pesticides, but the effect on the nitrogen compound balance is less obvious, mainly because of the greater use of organic materials of animal or urban origin (compost, slurry, manure, elaborated organic fertilizers) for crop fertilization.

As city dwellers become more and more removed from the agricultural world that previous generations once knew, cities have started moving closer to the countryside. The influence zones of urban areas are expanding and city boundaries are becoming increasingly blurred, creating urban fringes where the city merges into the countryside. While agricultural activities happen in agricultural areas, the people living there and the local economic activities are not always directly affected by them. "These are areas whose relatively low population density leaves a lot of room for fields and forests in land use, but not necessarily for agriculture in economy and in society." (Lévy and Lussault 2003).

Air pollution is only one aspect of the many issues, relationships and reconsiderations associated with certain agricultural practices. While air pollution is often not very visible or well identified, it plays a part in reinforcing the image of intensive, industrial or even artificial agriculture. As mentioned above, agriculture is a key focus in terms of air quality due to pesticides and nitrogen compounds, which have been of major concern since the beginning of the twenty-first century. These issues are added to (and sometimes mixed up with, leading to confusion) a series of societal concerns on food – and therefore agricultural production. These issues include bacterial contamination, the mad cow crisis or animal welfare, and stem from more or less well-founded fears and a rejection of certain production methods. Paradoxically, this distance from the agricultural world is accompanied by a passion for the countryside and a real need for proximity to "nature".

3.1 Rural Areas Are Undergoing Major Demographic and Economic Shifts

The areas used for agriculture and livestock farming reached their peak at the beginning of the nineteenth century in France, occupying more than 60% of the country. These areas then declined as forests developed on abandoned agricultural land, before rural areas were affected by massive soil artificialization due to the expansion of cities and transport infrastructures or various economic activities. However, agricultural land remains a highly structuring element of rural landscapes as well as peri-urban areas, where there are many interactions between various activities (agricultural, residential and industrial sectors, economic and commercial activity areas, transport routes).

Even though some 80% of the French population lived in cities in 2012, the built-up surface accounted for only 9% of the country's land areas, while agricultural soils occupied more than 50% and natural and forest areas 40% of mainland France. In 2009, 14.2 million people lived in rural areas, i.e. 22.8% of the population living across 78.2% of mainland France, with a low average population density (33 inhabitants per square km). Figure 4 illustrates the demographic dynamics in rural and peri-urban municipalities that have gained new residents as a result of people moving from urban to rural areas for various reasons (e.g. growth of tertiary jobs, de-industrialization of urban centres and suburbs, lower housing costs, better quality of life, development of urban fringes, better transport).

This process leads to a social reconfiguration of regions from city centres to peri-urban and rural areas. In his thesis, Pierre Pistre (2012) concludes the following: "Because of the scale of local migration from urban centres and the types of newcomers – working people under 50, couples with children, executives and highly educated professionals, white- and blue-collar workers – some of the changes in the French countryside have been part of well-determined processes of peri-urbanization or more diffuse urbanization. Other forms of rural demographic renewal have been characterized by more distant arrivals and older populations, retirees, as well as mid- to late-career working people." This last population movement mainly occurs in tourist regions and conceals issues about the future of more isolated regions.

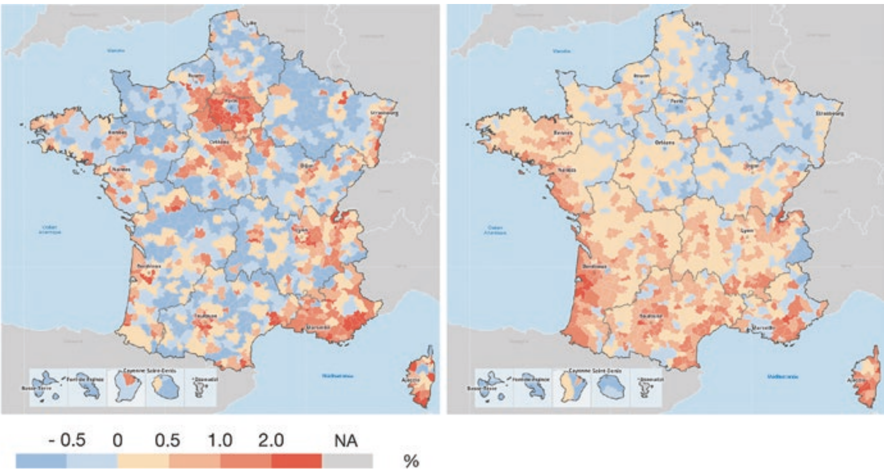

Fig. 4 Changes in annual population growth rates due to apparent net migration between 1968–1975 (left) and 2010–2015 (right) in France. (Source: INSEE, https://statistiques-locales.insee.fr/#view=map1=indicator)

These demographic changes show a contrast between the arrival of young populations, attracted by more space and being able to have a garden, and older former residents or retirees newly settled in appealing countryside areas.

3.2 The Consequences of Exposure among Rural Populations

As the interfaces between agriculture and other sectors of activity increase, a growing proportion of the population is being affected by the positive and negative externalities of nearby agricultural activities, without being directly involved in the activities themselves. In addition to the appeal of rural landscapes and local access to food, rural or peri-urban inhabitants may be subject to local disagreements over odours and atmospheric pollutants emitted directly by agricultural activities: applications of pesticides, livestock manure, compost, sewage sludge and mineral fertilizers as well as proximity to livestock buildings or animals in the field.

While still limited, the rising pollutant measurements at rural sites, suggest counterintuitively that country air is not always clean, despite air pollution in rural areas generally posing a lower public health risk due to relatively low air concentrations and low population density. For several decades, the Europewide European Monitoring and Evaluation Programme (EMEP) network and some French regional air quality monitoring associations (AASQA) networks and measurement campaigns have discovered that the countryside has not been spared by pollutants coming from elsewhere. All rural areas are affected by general background pollution, which can persist in the atmosphere for several days to weeks. Based on such data, the French Public Health Agency estimated that 8000 people died each year from air pollution in rural areas in France, for a population estimated at 14.2 million in 2009. Many young children are among the inhabitants of peri-urban areas who have fled the miasma of the city for open spaces and a garden. People living in rural areas are often elderly people who are remaining in their own homes or retirees attracted by the charms of the countryside. These two categories of the population are particularly vulnerable to pollution exposure. The pollution to which they are exposed is varied and comes from many different sources, and the interconnections between agricultural, residential and other activities can be considerable.

3.2.1 Pollutants Emitted Specifically by Agriculture

The sharp rise in the use of external inputs in agriculture has significantly increased pollutant emissions in the atmosphere. They primarily come from ammonia linked to fertilization practices and livestock activities, and pesticides that are mostly used for crop protection. Those working in agriculture are mainly exposed to these pollutants when handling the products or in agricultural buildings. However, the ambient air in rural areas is directly affected by these sources.

Agricultural activities contribute significantly to pollutant emissions. Its influence is even increasing in relative value due to measures to control other anthropogenic sources of acidifying compounds (NH_3, NO_x, and SO_2). As noted in chapters "Mechanisms of Pollutant Exchange at Soil-Vegetation-Atmosphere Interfaces and Atmospheric Fate" and "Measuring Air Pollutant Concentrations and Fluxes", agriculture generally produces diffuse emissions of low density (e.g. emission of ammonia or pesticides after field application) that are highly influenced by environmental factors (soil, climate). This often makes assessing them difficult and subject to a high level of uncertainty. Because agricultural emissions are diffuse, they tend to not be noticeable by local populations, except during pesticide spraying or when they produce odours (e.g. during and immediately following organic manure application), and which generally do not have any health impacts.

3.2.2 Effects Due to Proximity

When it comes to air quality, the distance to pollution sources is a key driver of pollutant concentrations in the lower atmosphere, and consequently, of exposure and impacts on ecosystems or health. The interconnectedness of residential areas and agricultural activities highlighted above increases the risks and can therefore lead to various impacts or even conflicts related to pesticide applications or odours. A typical example concerning air quality is the possible effects of pesticide application on the health of resident populations, or indirectly through the consumption of agricultural products exposed to these applications. It is likely that these relationships are intensified by the increase in urban populations living in rural areas. They face new contexts and problems, and must become aware of issues such as pesticides. The existence of more intense sources than previously observed (larger livestock facilities, widespread use of slurry-based systems, more pesticide treatments) can also affect these relationships. A survey conducted in Canada showed that about 60% of complaints about so-called "normal" agricultural activities came from urban populations; they mainly concerned odours, followed by noise and the use of "chemicals". However, the French Building and Housing Code specifically states that neighbours complaining about nuisances due to agricultural activities are not entitled to any compensation if the home is located in an area where the farm already existed and when agricultural activities are carried out in accordance with the law. This means that farmers who were already operating their farms before the arrival of the complainant are, in principle, protected by this legislation, but they must comply with all regulations specific to their activity (for example, rules on the application of slurry or pesticides). In addition, the "neighbour" may request that more stringent technical requirements be applied, and compliance with legislation and litigation may prevent certain developments within the farm.

3.2.3 Regions Particularly Concerned

As with water quality issues, environmental and health effects related to air quality are reinforced by the geographical concentration of certain agricultural products resulting in a hotspot effect: since the natural environment (including agricultural land) can only absorb part of the emissions, this leads to high levels in the atmosphere and impacts that are often more pronounced in or around these regions. Some concentrations in emitting areas result from traditional activities, as is the case in vineyard areas where particularly high pesticide levels have been observed due to repeated and simultaneous treatments on vineyard plots. Others are more recent and stem from changes in the agriculture and agri-food sector and regional development actions. This is the case of livestock activities, whose development resulted in large concentrations in western France in the second half of the twentieth century, in response to efforts to organize the sector, achieve economies of scale and support regional development (Peyraud et al. 2014). These concentrated activity areas, which often use large amounts of inputs, create regional hotspots of airborne emissions along with water quality problems, which cause or amplify the reactions of social actors and public policymakers.

3.2.4 A Rural and Peri-Urban World Exposed to Pollution from Nearby Cities and Non-agricultural Activities

In addition to their own emissions, densely populated peri-urban areas are exposed to various emissions from both rural and urban sources. Peripheral areas are often home to polluting facilities that must be located in less densely populated areas, either because of regulations (e.g. due to air pollution issues) or for ease of access. In addition to industrial sources located in rural and peri-urban areas, inhabitants themselves contribute to their own pollution exposure through their lifestyles (housing, travel, heating). Individual housing, which dominates in peri-urban areas, encourages behaviours that have consequences on polluting emissions. For example, wood heating is widely used as the main or supplemental heating method; gardening is a very widespread activity and leads people to handle various pesticides or fertilizers. But above all, because of the intensity of exchanges, these spaces require using cars, which is the main means of personal mobility, compared to the opposite trend of decreasing car use in cities. Road traffic is omnipresent in peri-urban areas, with consequences on air quality linked mainly to nitrogen oxide, VOCs and black carbon emissions.

3.2.5 Air Pollution Related to Interactions Between Urban and Rural Emissions

Finally, the ever-greater interconnectedness between agricultural activities and other sectors of activity in peri-urban areas, combined with anticyclonic meteorological conditions, leads to the concomitant accumulation of precursors from agricultural sources (NH_3) and road traffic (nitrogen oxides: NO_x), as well as industry (sulphur dioxide: SO_2). In France, this produced large-scale episodes of particulate matter pollution in March 2014 and March 2015. Nitrogen fertilization is particularly concentrated in late winter and early spring, in connection with vegetation recovery and crop growth. In these cases, ammonium nitrate can be the main component of measured PM2.5 and PM10 levels (Walker et al. 2004), which confirms the relevance of agricultural ammonia emissions at this time of year in terms of air quality issues.

The mixture of plumes formed by urban pollution and agricultural emissions also promotes reactions between NO_x (mainly urban origin) and BVOCs (rural origin) to form ozone. Ozone peaks extend over large areas and affect in particular peri-urban and rural areas (Stella et al. 2016), justifying the designation of ozone as a peri-urban pollutant.

Finally, ozone could amplify the allergenic potential of pollens (which are abundant in the peri-urban environment) by increasing the allergen content of pollen grains and their ability to be released into the air. Moreover, by irritating the respiratory tract and skin, pollutants facilitate the penetration of pollen allergens into the human body. It also seems that when pollen grains come into contact with certain gaseous pollutants, they can burst, which then creates even more particles (Monnier et al. 2015).

3.3 Societal Concerns About Agriculture Also Raise Questions about Air Quality

3.3.1 Crises on a Regional Scale

While initial concerns in the 1970s and 1980s in France focused on water quality issues, especially in livestock areas (western France) and field crop areas (Paris Basin), these concerns have since spread. They are, however, less precise, because they are more difficult to identify for greenhouse gas emissions (N_2O from crops, CH_4 from livestock) and air pollution (NH_3, pesticides). While other routes of human contamination (contact, drinking, food) – especially with regard to pesticides and nitrogen compounds – are considered more significant, the "air" component will likely become more important in debates among social actors (individuals, associations) and agricultural actors, particularly because it is less avoidable and manageable. Another issue linking water and air quality has emerged more recently: hydrogen sulphide (H_2S) emissions from green algae in Brittany or Sargassum seaweed in the West Indies (Chapter "Necessary Integrative Approaches").

3.3.2 Early Regulation, But with a Low Impact on Society

Various regulations attempt to tackle air pollution, from continental scales (e.g. Europe and peripheral areas) to very local scales (impact of industrial facilities on surrounding areas). From a historical point of view, agricultural activities in France, and especially livestock farming, have been subject to air quality-related regulations since the early nineteenth century (olfactory nuisances) when livestock farming activities could still be conducted in or just outside of cities. The imperial decree of 15 October 1810 "on factories and workshops that spread an unhealthy or unpleasant odour" formed the foundation of the legal framework governing the relationship between economic activities and their environment. This decree included pig farms among the businesses that required authorization from the Minister of the Interior. The decree indicated that the coexistence of interests required displacing the activity according to three classes of nuisances (the first included pig farms, the second cattle farms, and the third class did not pertain to nuisances to residential areas but rather those that had to "remain subject to police surveillance"). These issues are now less pressing since agricultural activities and most industrial activities are no longer conducted in cities.

3.3.3 Regulations to Mitigate the Effects of Proximity

Point sources such as livestock buildings or field applications of manure or pesticides may have had a greater impact and a lower level of acceptability for local residents. One reason is that it is easier to directly link a visible practice or activity to nuisances or, where applicable, symptoms. Regulations have also been established to limit some of these activities near residential areas (decrees on livestock manure spreading). Such regulations are also a way to protect sensitive ecosystems (Hicks et al. 2011). While the issue of spreading livestock manure no longer seems to pose any major health problems other than odour-related inconveniences, pesticide applications near residential areas became a flashpoint in the public debate in the 2010s, particularly following pesticide applications used in conventional and organic agriculture near schools in the Bordeaux vineyards in 2016.

3.3.4 Wide-Scale Regulations

Air quality regulations at large scales (country, continent), especially in the context of the CLRTAP (see section on "Regulations and public policies" below), explicitly took agriculture's contribution to air pollution into account from the beginning, since the aim was to identify the full range of harmful human activities. In regulatory terms, the public authorities look at agriculture the same way they do at other anthropogenic activities to assess its sources and set reduction targets. This approach is quite similar to how greenhouse gas emissions are handled.

At the European and national levels, ammonia emissions are regulated (see next section) and have been discussed since the end of the twentieth century in national and international expert groups, which develop recommendations and best practice guides for limiting these emissions in order to comply with the negotiated emission ceilings. Pesticides are not currently regulated for air quality, but growing concern among societies and public authorities on these various compounds has in recent years led to an increase in the monitoring of concentrations in the atmosphere in some countries. For example, a national campaign to measure pesticide residues in the air, involving ANSES, INERIS and Atmo France was launched in France, in 2018. It was based on a harmonized protocole throughout the country.

3.4 A Multi-actor Approach to Implementing Regulations

The actors involved in pollution regulation and action differ according to scale. National level stakeholders are mainly public policymakers, i.e. ministries and the national public agencies and institutions that the ministries ask to handle such responsibilities. In France, these include ADEME, INERIS and several research institutes such as INRAE, CNRS and various universities (see Fig. 6). The agricultural industry stakeholders mainly contribute through national organizations providing expertise (technical institutes, chambers of agriculture, public research). Some environmental or consumer associations, such as France Nature Environnement, the association Respire or the Association for the Prevention of Atmposheric Pollution (APPA), have put air pollution on their agendas and are supporting national debates and actions, particularly in the field of agriculture. Their activities with the public also play an important role in dissemination and pedagogy, because the challenges are both complex and involve multiple criteria.

Local actors play an important role when it comes to implementing emission reduction methods. Farmers and even agricultural advisors are still not fully aware of the problem of farm emissions and the impact of air pollutants on production. Awareness-raising actions through national or regional information meetings or demonstration projects to improve understanding of the issues are necessary, in addition to possible actions to implement in line with other environmental issues and farm work. Various projects specific to air quality in agriculture are being rolled out across France through regional pilot projects.

At the regional level, institutional and economic actors interact more directly, for example in working groups to establish regional air quality plans or for the implementation of local actions (including research-action projects). At a more local level, there are proportionally fewer elected officials from the agricultural sector, and mayors are more likely to express the wishes of city residents who seek to maintain a quiet village atmosphere. In small agricultural regions, or even municipalities, groups of citizens may appear, often supported by environmental and media associations, which place concerns within a broader context. These actions can have national implications. This dichotomy is found in other environmental problems in soils, ecosystems or water, but the atmosphere is different in that the problems are less marked by local distinctive features (soil types, hydrological network, land use, etc.) and therefore more easily transposable and comparable from one situation to another.

3.5 An Activity Sector Impacted by Air Pollution, Yet Mostly Unaware

One thing that makes agricultural activities different to other activity sectors is that crop production itself is impacted by air pollution. Not only is ground-level ozone a problem, but deposits of metallic trace elements or organic micropollutants, often in the form of particles, from roads or industrial activities are also an issue. Civil society and agricultural actors are still not fully aware of the problem, even if recent alerts, publicized by the media, have made people more aware of the extent of ozone phenomena. This is a regional to continental pollution problem that concerns all sectors because of their emissions of ozone precursors (NO_x, VOCs, etc.).

At a very local level, the proximity of certain sources of air pollutants, such as industry or high-traffic roads, can render a significant portion of agricultural land unsuitable for certain types of production, either due to a risk of exceeding certain contamination standards, restrictive specifications regarding proximity criterion (e.g. for baby food), or the image for consumers (Petit et al. 2009). Some specifications impose safety distances of 250 m around roads, but the scientific basis is not clearly established. Various studies that measured the deposition of pollutants from major roads have indicated impact distances of a few dozen metres (Loubet et al. 2011; Petit et al. 2013). If this type of risk assessment were to become widespread, it would impose severe constraints on agricultural activities on the outskirts of large urban areas.

3.6 Summary

Awareness of agricultural air pollution has increased significantly in recent decades, with the issue of pesticides in the atmosphere, the contribution of ammonia emissions to the formation of secondary particles and very local indirect phenomena such as H_2S emissions related to the decomposition of green algae or Sargassum seaweed. Pollution from agricultural sources is quite different to the pollution encountered in cities. More specifically, nitrogen pollution is mainly connected to livestock activities and is made all the more visible by the fact that it is accompanied by olfactory nuisances, and pesticides are becoming increasingly visible in the media and through the actions of environmental associations. These problems are compounded by several factors. First, the general public has a more negative image of agriculture, which is associated with various nuisances caused by a shift towards an industrial-type activity. This poor image is also maintained due to agricultural and non-agricultural activities becoming ever more interwoven in rural areas because of the sharp decline in agricultural assets and a relatively recent migration from the city to the countryside outside major urban areas.

Although agriculture is vulnerable to air pollution, this issue must also be linked to climate change, whose consequences will require agriculture to adapt, namely because of the possibility that high ozone levels could be more frequent. Debate and proposed actions to limit emissions of air pollutants must be closely tied to greenhouse gas emissions as part of the policies and measures put in place. Moreover, some pollutants such as ozone and particulate matter (called short-lived climate forcers) have effects on the climate, despite having shorter lifespans than greenhouse gases. Controlling them is urgent and would mitigate both air pollution and climate change.

4 Regulation and Public Policy

4.1 Considering Air Quality in an Agricultural Context

While policymakers began including agriculture in air quality regulations rather late, certain major agricultural pollutants (ammonia and fine particulate matter PM2.5 in particular) have been increasingly regulated since the early twenty-first century (Fig. 5).

4.1.1 Initial Efforts to Reduce Pollutants of Agricultural Origin at the Source

The first observable link in regulations on air and agriculture appeared in the United States with the federal government's 1935 Soil Conservation Act. The law's measures aimed to limit wind erosion, a major source of dust.[3] Historically, the post-war period was one in which intensive agriculture and industry developed considerably in much of the world. These new high productivity systems were quickly regulated in France, and especially through a 1976 law on establishments classified for environmental protection (IED: industrial emission directive). Large ivestock farming facilities were included due to their ammonia emissions.

[3] Following the Soil Conservation Act, several regulations around the world were developed after the war to decrease polluting emissions: the Clean Air Act in Great Britain in 1956; the Clean Air Act of 1963 and the Clean Air Act Extension of 1970 in the United States; the SO_2 Emissions Act in Sweden in 1968, among others. These laws mainly targeted sulphurous and particulate pollution of industrial origin, as well as automobile pollution (United States 1970). They did not take agriculture into account and are therefore not discussed in further detail here.

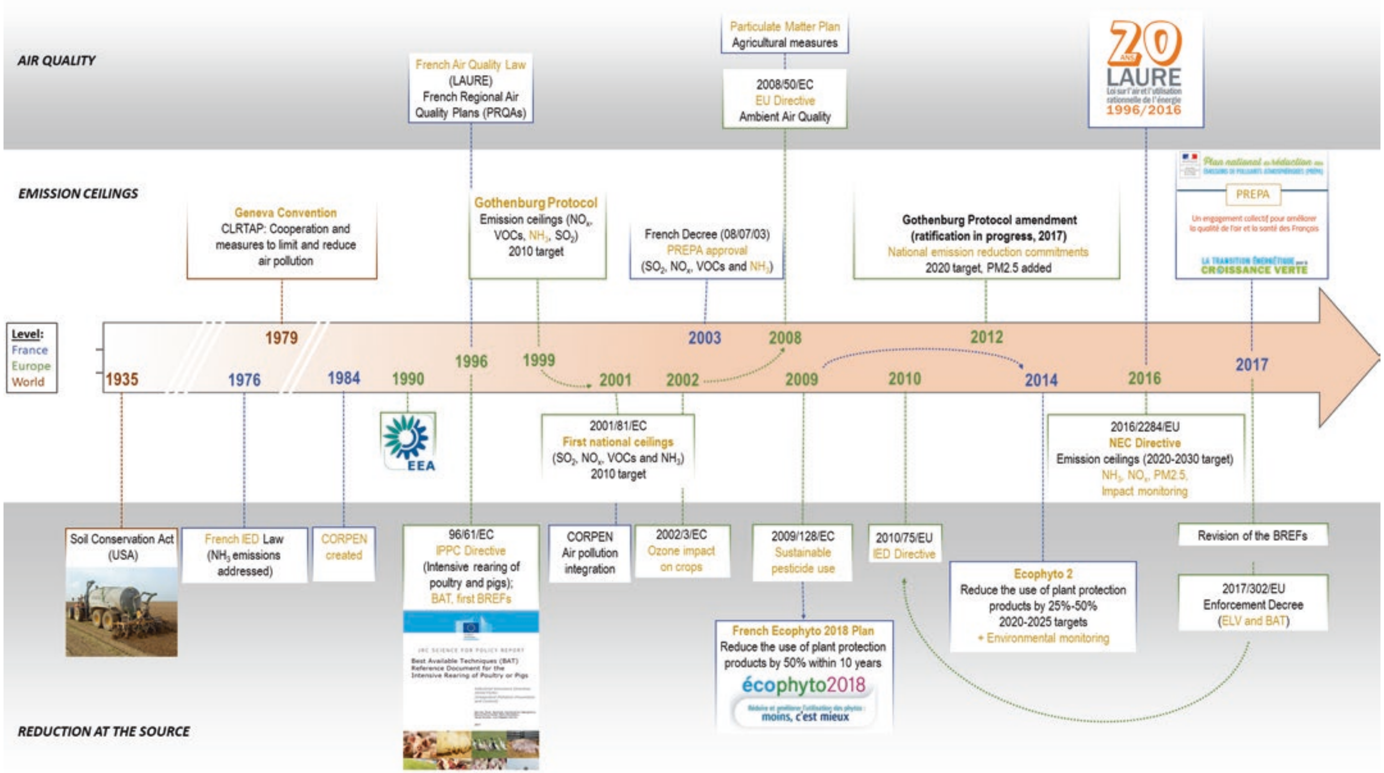

Fig. 5 Timeline of the process to integrate agriculture into air quality regulations

Twenty years later, the European Integrated Pollution Prevention and Control (IPPC) Directive 96/1/EC, was adopted and covered, among other things, intensive pig and poultry buildings, with a target of reducing pollutant emissions at the source. This directive puts forward a list of best available techniques (BAT) to be implemented and led to the publication of the first Best Available Techniques Reference Documents (BREF) in various industrial sectors, including livestock (BREF IRPP, Intensive Rearing of Poultry and Pigs). In 2010, the IPPC Directive was included in the Industrial Emissions Directive 2010/75/EU. A further revision of the BREF IRPP has been finalized and conclusions on BAT have been adopted through Commission Implementing Decision (EU) 2017/302. For the first time, ammonia emission limit values are given for livestock buildings, in connection with BAT for agricultural holdings.

At the French level, the Steering Committee for Environmentally Friendly Farming Practices (Corpen[4]), has been issuing recommendations on farming practices since 2001, integrating air (and soil) into its field of action. Pesticide-related pollution was a part of Corpen's scope of action in 1992, but was not really included in regulations until 2009 following the Directive 2009/28/EC, which France implemented nationally through its Ecophyto 2018 plan. This ambitious programme aimed to reduce pesticide use by 50% by 2018 and set up a network of experimental farms (Dephy). At the halfway point in 2014, the plan was updated as the Ecophyto II plan and the "50% less" target was postponed to 2025.

4.1.2 Integrating Agriculture into National Emission Ceilings

At the international level, awareness of the risks associated with air pollution was confirmed by the 1979 Geneva Convention on Long-range Transboundary Air Pollution (CLRTAP). This convention provided the framework for the first international cooperation and measures to limit and reduce transboundary air pollution through the establishment of national emission ceilings. In the 1990s, two key developments provided a more concrete framework for air quality monitoring systems, but did not specifically integrate agriculture. On the one hand, the European Environment Agency was created to give Europe an independent organization providing targeted, relevant and reliable information to policymakers and the public through the creation of the European Environment Information and Observation Network (EIONET). In France, the 1996 the Air and Rational Use of Energy Act (LAURE) introduced regional air quality plans (PRQAs) and established the geographical and technical scope of the regional air quality monitoring associations (AASQAs).

[4] The Corpen was created in 1984, but did not include air at the time (only agriculture-related water pollution). This committee, tasked with offering analyses, expertise and proposals, is meant to be neutral and objective.

The 1999 Gothenburg Protocol (which stemmed from the CLRTAP) laid the foundations for taking agriculture into account in air quality. It set the first emission ceilings for United Nations Economic Commission for Europe (UNECE) member countries to achieve by 2010, namely for ammonia. In Europe, this led to Directive 2001/81/EC, which reduced the national ceilings for certain atmospheric pollutants. Two years later, France adopted its first national emission reduction plan (PREPA). In particular, the goal was to reduce SO_2, NO_x, VOC and NH_3 emissions and develop local Atmosphere Protection Plans (PPA) created by the LAURE Act. In 2008, at European level, several air quality directives (including Directive 2002/3/EC relating to ozone in ambient air) were updated and unified in Directive 2008/50/EC on ambient air quality and cleaner air for Europe. This directive was transposed into French law through the Particulate Matter Plan, which aimed to reduce background particulate pollution (30% reduction in PM2.5 by 2015) consistently across all emitting sectors, including agriculture.

Along with these various directives, two key changes reinforced the regulation of emission ceilings in the agricultural sector:

- In 2012, the Gothenburg Protocol was amended and fine particulate matter (PM2.5) was added to the list of monitored and regulated pollutants. National emission reduction commitments were reviewed (timeline set for 2020).
- In 2016, the National Emission Ceilings Directive (NEC, 2016/2284/EU) was published, reinforcing ammonia emission ceiling reduction objectives by setting a new target to achieve by 2030 compared to 2005 levels, with the addition of systems for monitoring the impacts on ecosystems. A ceiling on methane emissions, more than half of which come from agriculture in France, was also considered, but not retained.

The 2003 PREPA was then updated to comply with the new ceilings. However, the decision was made to include France's national targets and its national programme directly in the French Energy Transition Act (2015) to enhance their visibility. This "new PREPA" links the definition of emission ceilings and pollutant reduction objectives at the source: it sets out guidelines and actions for the 2017–2021 period for all activity sectors, including agriculture, as well as emission ceilings to be achieved between 2020 and 2030. With regard to pesticides, the French Ecophyto II plan also included an environmental monitoring component to monitor the presence of pesticides in the various environments, including air, through the implementation of a national exploratory campaign in 2018. Intensive agriculture is beginning to be rethought, and alternative systems that use fewer and less-polluting inputs are becoming more visible in public policies (e.g. agroforestry, organic farming). The main regulations in force in 2019 are detailed in the following section.

4.1.3 The Regulatory Framework in 2019

Air pollutant emissions from agriculture are regulated by a regulatory corpus mainly defined at international and European level, which is adapted and transposed into national and local laws.

At the international level, the Gothenburg Protocol sets out national emission ceilings for SO_2, NO_x, VOCs, NH_3 and PM2.5 based on environmental quality objectives for ecosystems (critical loads of acidity and nutrient nitrogen and critical levels of ozone). The Protocol was amended on 4 May 2012 with new reduction commitments for 2020 compared to the 2005 baseline year (e.g. a 4% reduction for ammonia). In 2019, this amendment was still in the process of being ratified.

At the European level, two directives explicitly address the issue of air quality. The Air Quality Directive 2008/50/EC sets thresholds for concentrations of PM10 and PM2.5 particles and nitrogen oxides, as well as a target of a 20% reduction in exposure to PM2.5 between 2010 and 2020. Meanwhile, Directive 2016/2284/EU (known as the National Emission Ceilings (NEC) directive) set out the national emission ceilings in each Member State for SO_2, NO_x, NH_3, NMVOCs and PM2.5 by 2020 and 2030. When the NEC Directive was revised, a threshold on emissions of CH_4, an ozone precursor that comes primarily from agriculture (70%) and mostly from livestock, was also considered. NH_3 and dust emissions from livestock farms are also regulated through the IED 2010/75/EU. In particular, the IED requires poultry farms (with more than 40,000 head) and pig farms (with more than 2000 fattening pigs or 750 sows) to report their emissions, to comply with ammonia emission limit values at farm building level and to apply the best available techniques, including for storage and spreading of animal waste. Including cattle farms within the scope of the directive was also considered. However, ultimately they were not added because the environmental benefits were estimated to be limited to costs related to administration and building compliance upgrades, which are potentially significant for a large number of agricultural holdings (COM/2013/0286 final).

These European regulations have been transposed into French law through various laws, decrees and orders. In particular, the French decree of 10 May 2017 sets out the PREPA measures as imposed by Directive 2016/2284/EU. These measures specifically deal with agricultural emissions and include restrictions on the use of urea between February and April; the implementation of an action plan to eliminate the use of the most emissive spreading equipment by 2025; and the development of alternative methods and techniques to burning of agricultural residues in the field. Although the presence of pesticides in the air is not regulated at European level, France plans to monitor them in ambient air from 2018 as part of its Ecophyto II plan and the PREPA. The measures implemented under the Ecophyto II plan to reduce the use of pesticides by 50% are also expected to limit their presence in the atmosphere. For example, the Pesticide Savings Certificate Scheme (CEPP), modelled on energy savings certificates, includes an action sheet entitled "2017-003 Reducing the dose of pesticides using recovery panels in viticulture", which has an effect on both use and losses into the atmosphere (French Decree of 9 May 2017 defining standard pesticide savings actions). Finally, the post-homologation monitoring in the atmosphere can be used by ANSES to assess the harmfulness of active substances.

Regional and local authorities in France take action through Regional Climate, Air and Energy Schemes (SRCAEs), Territorial Climate-Air-Energy Plans (PCAETs) and Atmosphere Protection Plans (PPAs). The SRCAEs aim to establish an integrated approach that takes into account regional priorities for climate, air and energy. The PCAETs require public inter-municipal cooperation establishments (EPCIs) of more than 20,000 inhabitants with their own taxation to translate these guidelines into actions at the local level that must be reviewed every 6 years. PPAs establish measures to be taken to reduce emissions within a given scope (e.g. conurbation, area with excess inputs) in line with the Air Quality Directive. Regional Plans for Sustainable Agriculture (PRADs) aim to ensure the coherence of these actions for the agricultural sector. The Farm Competitiveness and Adaptation Plan (PCAE) is the main support mechanism to help farmers make investments to reduce emissions (e.g. spreading equipment, sprayers). It is linked at regional level to Regional Rural Development Programmes (PDRR), submitted by each region to the European Commission.

4.2 *Public Policies and Air Quality: Multiple Interactions*

The general interactions between the main actors are detailed in Fig. 6, and briefly illustrated by two key examples showing how agriculture is taken into account in air quality regulations: ammonia and pesticide pollution.

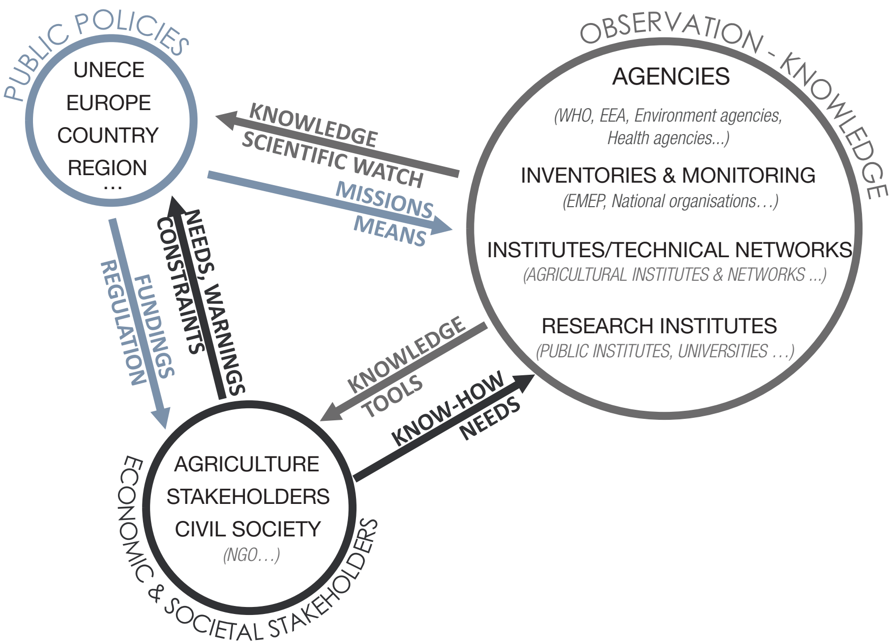

Fig. 6 Interactions between the different actors involved in taking agriculture into account in air quality regulations. The sizes of the circles are not proportional to the importance of the actors

Ammonia pollution is a good example that reflects the various actors involved in developing the current regulations. Since the late 1970s, the increasing acidification of natural environments (acid rain, of which ammonia is one of the causes, along with sulphur dioxide and nitrogen oxides) troubled governments around the world. Several States met and ratified first the Geneva Convention (1979), which aimed to limit transboundary pollution. Then, at the European level, the IPPC Directive (96/61/EC) set reduction targets at the source and proposed best available techniques. Finally, the Gothenburg Protocol set emission ceilings to be met in the future. International targets were implemented at European and national level through various laws and decrees (e.g. the approval of the PREPA in 2003 in France). Regional schemes were then developed according to local contexts. Meanwhile, research organizations and institutes also received funding in order to gain insight into the relevant phenomena (emission, transformation, risks) and provide innovative solutions to achieve the ceiling targets. This research was partly carried out in the field, in conjunction with agricultural professionals, in order to better integrate the constraints linked to farming systems in different emitting chains (pigs, poultry, cattle). Inventory and monitoring networks as well as air quality monitoring associations participated in the process by providing data and advising public authorities in case of risks (such as pollution peaks).

The general public is not very aware of such measures to control ammonia emissions due to weak media coverage of a topic that only marginally affects peoples' daily lives.[5] However, for pesticides, demands for action and warnings have partly come from international bodies such as the WHO as well as local citizens' associations and have been covered in the media.[6] Some states and Europe then began directing funding to research organizations. This rising environmental and health awareness along with changes in consumer demands have reinforced the visibility of the "Organic Agriculture" label, which is now being used internationally. At the national scale in France, the Ecophyto plan (and later Ecophyto II) was launched to specifically address this issue over the long term at all levels (research, action, awareness, air quality monitoring, reduction targets), while the agricultural industry is adapting to not only protect users (farmers, pesticide applicators) and the environment, but also to provide food that meets consumers' expectations. These plans are based on research results and help gather feedback on knowledge and field experiences to improve crop management and raise technical difficulties related to new regulations (e.g. prohibition of active substances, dose reduction).

[5] https://www.theguardian.com/environment/2016/may/17/farming-is-single-biggest-cause-of-worst-air-pollution-in-europe

[6] For example, see https://time.com/5555300/pesticide-exposure-autism/ or the article published on francetvinfo.fr relaying the work of the association Générations futures, https://www.francetvinfo.fr/sante/environnement-et-sante/les-riverains-des-champs-exposes-aux-pesticides-selon-generations-futures_1340247.html (available in French only)

4.3 Consistency with Other Public Policies

Today, agriculture is no longer viewed strictly from a food production perspective. It is increasingly subject to many public policies on health, environmental quality (water, air and biodiversity), climate change, renewable energy development and animal welfare (Fig. 7). These public policies set guidelines and issue recommendations or even obligations. While some are well established in the agricultural industry, such as those related to water quality, others are quite new, such as those on climate change or air quality. The accumulation of policies and measures can lead to inefficiency and sometimes resistance from professionals, especially if they are not sufficiently coordinated and have major inconsistencies (Cellier and Génermont 2016). There are also risks of conflicting effects from different policies, which can result in transfers of pollution and impacts. Oenema et al. (2009), for example, showed that measures to limit NH_3 emissions (air quality) through manure pit covers could have a negative impact on nitrate leaching (water quality), N_2O emissions (climate) or CH_4 emissions. Policymakers must look beyond monothematic measures to tackle these challenges in an integrated and multi-scale manner, proposing trade-offs between the different issues when relevant.

This is why, for example, international efforts were made in recent years within the framework of the CLRTAP to establish an integrated multi-impact approach to nitrogen,[7] or the Climate & Clean Air Coalition initiative[8] (Lode 2014). At the national level, France's agroecology project (2012) aims to support the development of economically viable and environmentally friendly production systems, namely by promoting better biogeochemical cycle closure (water, nitrogen, carbon etc.) and biodiversity conservation. The PRADs also enable the French State and regional authorities to define guidelines integrating the various agricultural issues, even though the regions are now the managing authorities of the European Agricultural Fund for Rural Development (EAFRD). As such, they are responsible for organising, as lead partners, the procedures for public action on air quality issues, climate, energy and biodiversity protection (French Act no. 2014-58 of 27 January 2014). The development of medium- and long-term prospective scenarios for agriculture co-constructed with the various stakeholders and their assessment of the various environmental aspects can encourage actors to share challenges and help define common areas for action. For example, the Afterres2050 scenarios produced by Solagro (an agricultural consulting association) provide quantified data to initiate a multidisciplinary debate in order to address many interrelated challenges, with variants to better understand the impact of modelling options[9] (e.g. rebalancing the diet, artificializing the soil, reducing livestock and extensification of systems).

[7] Task Force on Reactive Nitrogen, http://www.clrtap-tfrn.org/

[8] https://www.unenvironment.org/explore-topics/climate-change/what-we-do/climate-and-clean-air-coalition

[9] The modelling matrix developed and used by Solagro (MoSUT) was also used by ADEME to define the 2030–2050 trajectories discussed during the preparation of the French energy transition law.

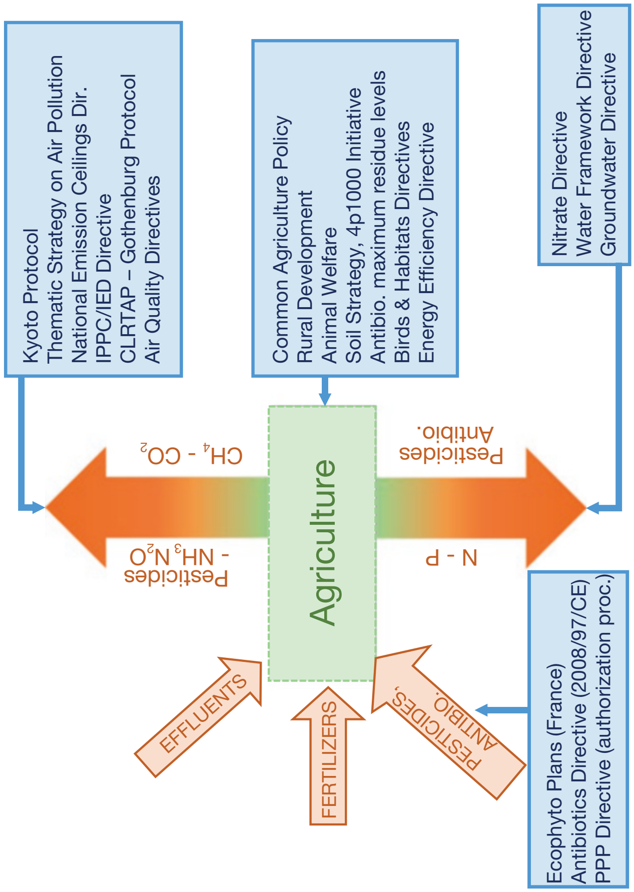

Fig. 7 Diagram of interactions between different public policies. (According to Oenema et al. 2009)

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