whether microglia are also involved in the process remains unknown. Indeed, microglial cells, which also express adenosine receptors, play an essential role in synaptic pruning (*13*). Motile microglial processes make brief contacts with synaptic structures to sense immature synaptic activity and physically remove the defective synapses (*13*). Therefore, an interesting matter for future study would be to understand whether adenosine, acting on $A_{2A}R$, may serve as a coincidence activity detector to coordinate the roles of neurons and microglia in this pruning process.

Imbalances in the adenosine pathway (i.e., enhanced extracellular amounts of adenosine and $A_{2A}R$ up-regulation) have also been demonstrated in the aged brain as well as in epilepsy, neurodegenerative, and psychiatric disorders. All of these physiological and pathological situations involve functional and morphological synapse remodeling. Compelling evidence demonstrates that the synaptic and neuronal up-regulation of $A_{2A}R$ in aging and neurodegeneration is instrumental to the decline of synaptic function and degeneration, presumably through neuron-glial dialog (*14*, *15*). The mechanism uncovered for synaptogenesis by Gomez-Castro *et al.* may have broader implications—e.g., that of adenosine possibly playing a more general role as an activity detector, regulating synaptic dynamics and presumably synaptic loss, in the aged and diseased brain (see the figure). Adenosine and $A_{2A}R$ would then regulate the fate of particular synapses in extreme stages of the brain life cycle. This supports a prime role for adenosine in synaptic allostasis (i.e., during brain adaptation to challenges), the controlling of brain network wiring, and cognitive function. ■

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PHOTO: HANS ENGBERS/SHUTTERSTOCK

Manure injection is a technology that uses less mineral fertilizer and reduces ammonia emission.

POLLUTION

How ammonia feeds and pollutes the world

It is cheaper to cut ammonia emission now than to deal with its consequences later

By **Jan Willem Erisman**

Ammonia, with the chemical formula NH_3, is a common ingredient in many industrial and agricultural applications and plays a pivotal role in producing the fertilizers needed to produce enough food for 7.9 billion people. However, the agricultural use of ammonia also negatively affects the environment, resulting in the loss of biodiversity and the pollution of water, air, and soil (*1*). Ammonia contributes to the formation of nitrous oxide, a powerful greenhouse gas, worsening the problem in most scenarios but also curbing it somewhat through cooling by aiding the formation of particulate matter and clouds (*2*). On page 758 of this issue, Gu *et al.* (*3*) show that the economic cost associated with the loss of human life—owing to ammonia's contribution to air pollution alone—far outweighs the economic cost to curb ammonia emission.

When released into the air, ammonia bonds with nitrogen oxides and sulfur dioxide and forms particulates less than 2.5 µm in diameter, known as $PM_{2.5}$. These particlulates can lead to premature death when inhaled. The World Health Organization (WHO) recently recognized air pollution as the single biggest environmental threat to human health and reassessed the impact of $PM_{2.5}$ on overall air-quality (*4*). Gu *et al.* report the annual cost of human life due to nitrogen-related air pollution to be 23.3 million years. For the sake of comparison with the monetary cost to curb nitrogen emission, this toll in human life can be interpreted as an economic cost of roughly US$420 billion. Based on these numbers, the authors present a quantitative argument for the reduction of ammonia emission. According to their analysis, the abatement cost for ammonia is only a fraction of the corresponding human life cost, as well as only 10% of what it would take to cut out an equivalent amount of nitrogen oxides (*3*).

Ammonia belongs to a group of compounds known as reactive nitrogen (N_r), which is the basis for the formation of amino acids—the building blocks of life. These compounds are available in nature to a limited extent. They can be released during volcanic eruptions and lightning and can be formed by the activity of nitro-

Institute for Environmental Sciences, Leiden University, Netherlands. Email: j.w.erisman@cml.leidenuniv.nl

gen-fixing bacteria, which is essential for the growth of plants and thus for the entire food chain, including humans. The ingenuity with which nature deals with the limited availability of these compounds has, over several millennia, led to the development of many natural processes and organisms and rich biodiversity.

The rapid economic development of the global economy over the past century has led to enormous growth in N_r production (*5*). Because of this artificial abundance of N_r in natural and agricultural ecosystems, some natural processes have become unnecessary, resulting in biodiversity loss, coastal eutrophication, acidification and eutrophication of nature areas, human health impacts, and stratospheric ozone depletion. A single molecule of N_r can be transferred from one system to another and contributes over time to all the different negative effects listed above, in what is known as the "cascade effect" (*6*).

Although much effort has been dedicated to the reduction of nitrogen oxide (NO_x) emission, Gu *et al.* argue that ammonia can provide a cheaper pathway for N_r reduction. They estimate the abatement cost of NO_x emission at US$16.0 per kilogram of nitrogen reduced, compared with US$1.5 per kilogram of nitrogen reduced by way of ammonia, and this can be achieved by using relatively low-tech solutions such as the reduction of fertilizer use and better management of manure storage and usage. Moreover, policies targeting NO_x reduction alone may not adequately slow down the increasing concentration of N_r in ecosystems and the atmosphere (*3*, *4*), and ammonia reduction may be the extra tool necessary to achieve these targets.

Ammonia from animal manure in livestock production alone contributes roughly 60% of the global ammonia emission and is increasing because of the rising demand for animal products (*7*). Global emission of ammonia has doubled since the 1960s. Ammonia has long been considered a local problem in intensively cultivated areas with concentrated livestock production, such as the Netherlands and Denmark. But, as satellites with infrared spectrometers continue to provide data on ammonia concentration in the atmosphere, the focus of studies assessing ammonia emission has since shifted to the global stage (*8*, *9*). Studies using these new data have indicated an overall underestimation of both anthropogenic and natural ammonia emission in the current data (*10*). These reports indicate that current modeling likely underestimates ammonia pollution, especially in high-intensity agricultural areas. These areas, being relatively close to human populations, may also amplify the negative effects on public health.

Although the Netherlands and Denmark reduced their ammonia emission by 60% over the past three decades (*11*), further reductions are necessary owing to the ruling of the European Court in 2018 that requires N_r emission to be reduced (*12*). Based on this ruling, the State Council of the Netherlands has since judged the Dutch nitrogen policy to be ineffective, resulting in what has become known as the "nitrogen crisis" (*11*, *12*). The council ruling drastically limits the availability of N_r emission permits across all sectors until enough N_r reductions have been achieved within the nation, and the economic loss has been estimated to be 14 billion euros (*12*). The nitrogen crisis in the Netherlands has shown that there needs to be a better balance between long-term sustainability of economy alongside ecology with respect to N_r emission.

The contributions from excess N_r to climate change, water pollution, biodiversity loss, and landscape quality need to be addressed. This will require changes that may disrupt the economy of food production and may require incentives and provisions to help farmers adapt (*11*). The ongoing economic shock in the Netherlands caused by the nitrogen crisis shows that nitrogen pollution can be quite expensive to fix if industrial, and especially agricultural, developments continue to progress unsustainably. Gu *et al.* show that the global burden of disease associated with nitrogen air pollution exposure is estimated to cause millions of deaths and lost years of healthy life annually and, together with economic setbacks, will cost far more to fix tomorrow than it would if action is taken today. ■

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ATMOSPHERIC SCIENCE

Midair transformations of aerosols

Spontaneous reactions play an important role in shaping the chemistry of aerosols

By **Manuel F. Ruiz-Lopez**

The presence of atmospheric aerosols, which are tiny solid or liquid particles suspended in the air, have a major impact on the global climate and public health. A wide variety of natural sources and human activities produce aerosols, ranging from volcanic eruptions to coal burning, which means that the composition of aerosols also varies greatly. Some of these aerosols can absorb or react with water vapor and other gaseous compounds while airborne. They influence the atmospheric chemical cycles (*1, 2*) and must be considered for improving current air quality and climate models. On page 747 of this issue, Kong *et al.* (*3*) describe an aerosol surface–driven reaction of great atmospheric relevance and suggest potential applications for the chemistry. They discovered that ammonium sulfate crystals exposed to water vapor would spontaneously form elemental sulfur and nitrogen gas on their surface at a much greater rate than expected (see the figure).

"...ammonium sulfate crystals exposed to water vapor would spontaneously form elemental sulfur and nitrogen gas on their surface at a much greater rate than expected."

Ammonium sulfate is an aerosol that can act as a seed for the formation of cirrus

Laboratoire de Physique et Chimie Théoriques, UMR CNRS 7019, University of Lorraine, CNRS, BP 70239, 54506 Vandoeuvre-lès-Nancy, France

Science

How ammonia feeds and pollutes the world

Jan Willem Erisman

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