Chapter

24

Future scenarios of nitrogen in Europe

Lead authors: **Wilfried Winiwarter and Jean-Paul Hettelingh**

Contributing authors: **Alex F. Bouwman, Wim de Vries, Jan Willem Erisman, James Galloway, Zbigniew Klimont, Allison Leach, Adrian Leip, Christian Pallière, Uwe A. Schneider, Till Spranger, Mark A. Sutton, Anastasia Svirejeva-Hopkins, Klaas W. van der Hoek and Peter Witzke**

Executive summary

Nature of the problem

- The future effects of nitrogen in the environment will depend on the extent of nitrogen use and the practical application techniques of nitrogen in a similar way as in the past. Projections and scenarios are appropriate tools for extrapolating current knowledge into the future. However, these tools will not allow future system turnovers to be predicted.

Approaches

- In principle, scenarios of nitrogen use follow the approaches currently used for air pollution, climate, or ecosystem projections. Short-term projections (to 2030) are developed using a 'baseline' path of development, which considers abatement options that are consistent with European policy. For medium-term projections (to 2050) and long-term projections, the European Nitrogen Assessment (ENA) applies a 'storyline' approach similar to that used in the IPCC SRES scenarios. Beyond 2050 in particular, such storylines also take into account technological and behavioral shifts.

Key findings/state of knowledge

- The ENA distinguishes between driver-oriented and effect-oriented factors determining nitrogen use. Parameters that cause changes in nitrogen fixation or application are called drivers. In a driver-based approach, it is assumed that any variation of these parameters will also trigger a change in nitrogen pollution. In an effect-based approach, as the adverse effects of nitrogen become evident in the environment, introduction of nitrogen abatement legislation requiring the application of more efficient abatement measures is expected. This approach needs to rely on a target that is likely to be maintained in the future (e.g. human health). Nitrogen abatement legislation based on such targets will aim to counter any growth in adverse environmental effects that occur as a result of increased nitrogen application.
- For combustion and industry, technical fixes for abatement are available. All scenarios agree in projecting a decrease in NO_x emissions. Yet agricultural nitrogen use is expected to remain the leading cause of nitrogen release to the environment, as options to reduce emissions are limited. Thus, major changes will occur only if the extent of agricultural production changes, which may possibly be triggered by decreasing population numbers in Europe. The scenarios presented here project modest changes in NH_3 and N_2O emissions, or nitrate leaching, but do not agree on the direction of these changes.
- Agricultural activity (and thus nitrogen loads to the environment) may decrease strongly if the European population adopts a healthier 'low meat' diet leading to lower nitrogen losses related to animal husbandry. Change to a 'healthy diet' across the EU, which consists of 63% less meat and eggs, would reduce ammonia emissions from animal production by 48%. However, if an agricultural area previously used for animal feed production is utilized for biofuel crops, additional nitrogen fertilizer may be required, which will partially offset reductions of nitrogen leakage to the environment.

Major uncertainties/challenges

- International trade in nitrogen-containing goods (agricultural as well as industrial) represents a key uncertainty and is difficult to project. Estimating the demand for such goods for Europe alone may not at all reflect European production and related environmental effects. The industrial use of nitrogen is also very poorly understood, but it is expected to continue to grow considerably. The respective environmental impacts of such products cannot be clearly discerned from statistical information.

Recommendations

- Scenarios need to be continuously updated in terms of economic, technical, and societal trends to reflect improved understanding of these factors. Using nitrogen budgets as tools could improve the consistency of scenarios.

The European Nitrogen Assessment, ed. Mark A. Sutton, Clare M. Howard, Jan Willem Erisman, Gilles Billen, Albert Bleeker, Peringe Grennfelt, Hans van Grinsven and Bruna Grizzetti. Published by Cambridge University Press.

24.1 Introduction

Scenarios developed for use in policy processes are intended to provide policymakers with insights into various possible futures based on a current understanding of the issues involved. Scenarios do not predict the future, but are made to provide decision support. Environmental scenario analysis typically addresses questions such as 'What will be the impact on the environment or human health in, say, 2050, of policy alternatives implemented in a base year (e.g. 2020)?'. In this chapter scenarios referring to external trends are called 'driver-oriented'. Conversely, scenarios can also be designed to identify the policies required to achieve predefined targets in the field of human or environmental health, referred to here as 'effect-oriented scenarios'. Economic and technological considerations form the basis of driver-oriented scenarios, while effect-orientated scenarios use an environmental target to arrive at a particular future situation. Scenarios may or may not capture developments which, with hindsight, seem evident. However, as demonstrated in integrated assessment modeling (Hettelingh *et al.*, 2009), they provide the only systematic approach to considering the possible consequences of policies for future events.

In Europe, a few scenario approaches have been developed that deal with the future fate of nitrogen (N) in the environment. We introduce and discuss several of these scenarios here. Obviously, the rate of change, and especially the probability, of 'technology leaps' (i.e., drastic changes beyond an extrapolation of the current development) increase when observed over an extended time range. The strategy for creating such a scenario may thus also change.

This chapter attempts to identify and quantify the most important influences on future developments in relation to application and release of N into the environment. It also touches on the uncertainty involved in any such expectation, recognizing that the lack of knowledge regarding uncertainties is even greater than that related to the scenarios themselves. Comparison of the different sets of available data indicates the range needing to be considered. However, as abrupt and unexpected changes are not covered at all, they obviously cannot show up in an assessment of uncertainty. Here, rather than developing and inventing new approaches or scenarios, we will review the material for Europe that already exists.

Figure 24.1 illustrates the multiple interactions between economic activities, the release of trace compounds and their subsequent fate in the environment, the adverse effects of the compounds, and the emission/release control targeted to resolve the adverse situations. Boxes shaded green refer to processes directly linked to N; arrows indicate only the most important pathways within the 'nitrogen cascade' (Galloway *et al.*, 2003). The 'driver-oriented' scenario uses information on economic activities and attempts to predict the environmental effects; the 'effect-oriented' scenario defines targets for environmental protection and then identifies emission control and activity numbers compatible with that target level.

Based on these interactions, we will first describe the concept of driver-oriented scenarios (Section 24.2) and effect-oriented scenarios (Section 24.3). Their potential use is discussed for short- and medium-term scenarios (Section 24.4), as are their implications for long-term scenarios (Section 24.5). Section 24.6 concludes with the results from a number of scenario activities available for the European Union (EU).

24.2 Driver orientation

24.2.1 The concept of 'drivers'

The extent of an economic activity and the changes in this activity over time can often be characterized by the parameters underlying that activity. If those parameters also describe a causal relationship, they are called 'drivers'. Ideally, statistical information on drivers would be easily accessible, as would information regarding their future development; thus, a change in their scope would lead to a proportional or at least predictable change in the economic activity in question.

Drivers of environmentally relevant activities may be classified according to their proximity to describe the respective economic activity. For example, Nowicki *et al.* (2006) distinguish exogenous drivers (demography, macroeconomic growth, consumer preferences, and technological development) from policy-related drivers (agricultural, trade, or climate policies). Likewise, one can distinguish primary drivers from secondary drivers, with the primary drivers (e.g. population numbers) influencing secondary drivers (e.g. food production).

For the purposes of this chapter, it may be useful to describe drivers with regard to specific topics (Table 24.1). These topics, each covering several drivers, will be covered in more detail in the sections below. For the scenarios, we distinguish strictly between drivers and policy action, with policy action seen as affecting the release of adverse substances over and above the developments initiated by the drivers.

24.2.2 Population

Food protein is essential to human metabolism. One of the constituents of protein is nitrogen, which is found in agriculturally produced food or in feed crops that become partially converted into animal products.

The number of people requiring food determines agricultural demand. Population numbers for European countries can be predicted with quite high confidence. Statistical lifetimes are stable and, compared with the timescales of the scenarios in question, are long. Reproduction rates, which are dependent on fertility rates and the size of the female population in certain age groups, are also well known. Even fertility rates, which affect population numbers over a longer timescale, change only gradually in stable societies. Population forecasts, a key element in any public and governmental planning, are the subject of detailed study. For Europe, UN (2004) statistics predict a population of 630 million in 2050 and 540 million in 2100, down from 730 million in 2000. These numbers include assumptions regarding migration, which is much more difficult to estimate, as demonstrated by the example of Spain where the population grew unexpectedly from 40 million in 2000 to 46 million in 2008 (EUROSTAT, 2009), mainly as a result of migration.

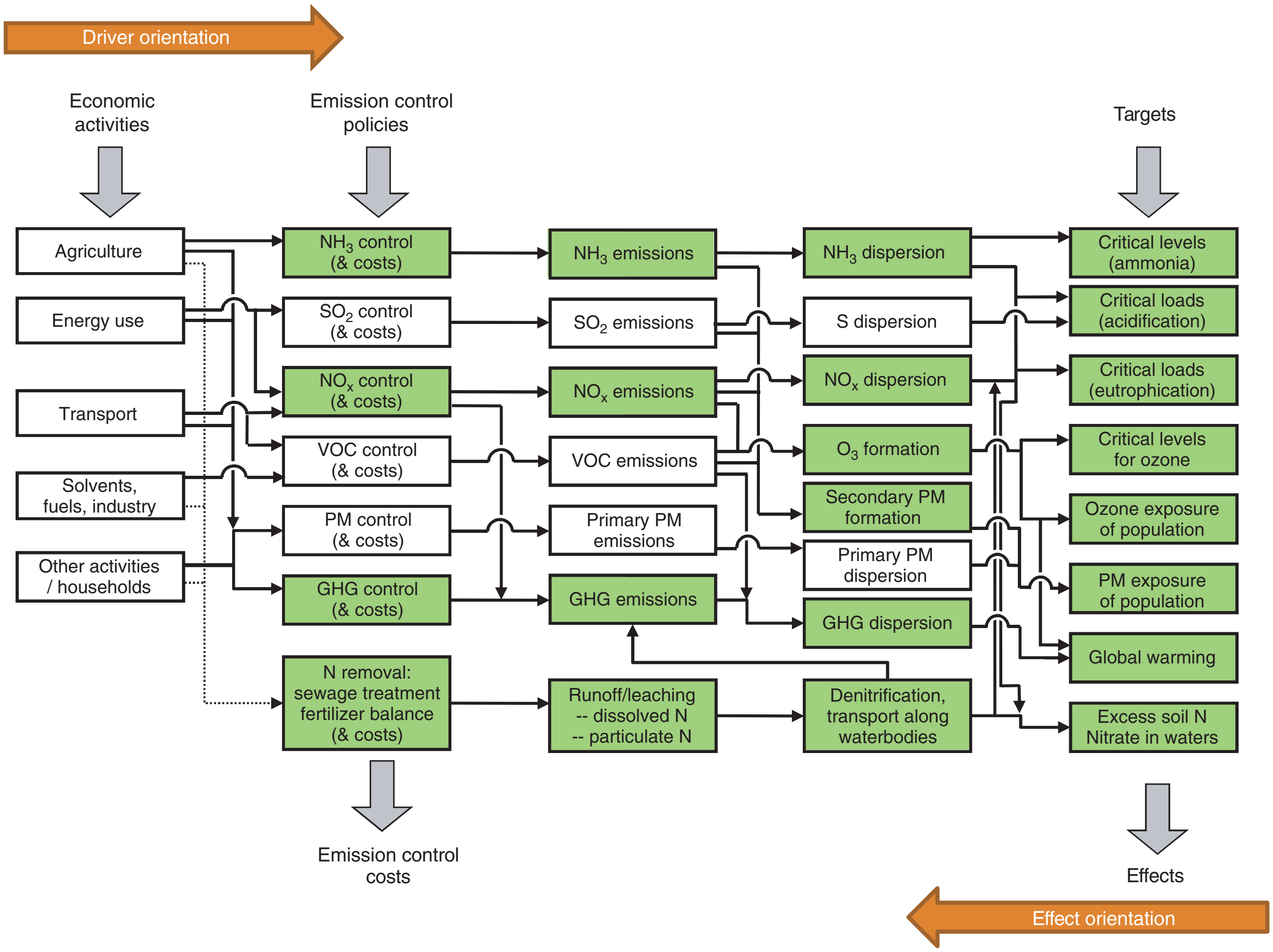

Figure 24.1 A schematic overview of the links between drivers and effects of environmental trace constituents in connection with nitrogen (boxes in green shading are directly linked to N).

Table 24.1 Drivers – important parameters for determining environmental nitrogen load

Topic	Driver
Population	Population number/change (birth rate, migration) Food choice (driven by income, health, dietary preference specifically regarding meat)
Land use	Cropland area Land loss to urbanization Loss to desertification, erosion, climate change Biofuel production
Fertilizer application	Agricultural demands (production) Agricultural technology/management Energy price and fertilizer price
N in combustion and industry	Industrial uses of Haber–Bosch nitrogen Reactive nitrogen in combustion
Markets	Trade liberalization (import/export) Global trade ('nitrogen leaking')

The nutritional habits of the population are also relevant. Europeans in general receive sufficient nutrition; food is available in abundance and, in favorable economic circumstances, frequently wasted. For Toronto, Canada, it has been estimated that about 30% of all food available at retail level is not consumed (Forkes, 2007), which also means that roughly a third of all agriculture, and thus a third of the nitrogen applied to agricultural soils, is wasted (assuming no difference in protein share

Table 24.2 Land use impacts on the nitrogen cycle

Land is required for:	Relevance for the N cycle:
Urban areas: housing, living, working	Release of reactive N in industrial and domestic effluents (air pollutants, sewage)
Water for recreation, fishing and water supply	Receptor of long-range transport N (deposition) and/or from run-off of NO_3
Nature, recreation, biodiversity	Receptor of long-range transport N (deposition)
Carbon sequestration	Influenced by nitrogen deposition and agricultural management (fertilization)
Agriculture: crops, livestock	Multiple use and losses of reactive N to different compartments
Transport of water, food, goods, people	Emission and transport of reactive N
Resources: energy, raw material, fiber	Uses and emissions of reactive N

between waste and used product). Similar but somewhat lower figures are available for the United States (27%: Kantor *et al.*, 1997) and Sweden (20% in food service institutions: Engström and Carlsson-Kanyama, 2004). Food wastage in Europe has been discussed in more detail by Resy *et al.* (2011, Chapter 26 this volume) as a 'societal choice'. These authors arrive at very similar conclusions with food wastage at a levels of 20%–30% of purchased food.

The choice of human diet plays an important role. The question of the conversion efficiency of meat production in terms of nitrogen has been covered in great detail by Smil (2002). Animal protein is available in the form of meat, milk, and eggs. Conversion efficiency varies strongly among different meat types. In the food chain, losses of protein are highest for beef (4% efficiency, or 96% loss), and lowest for milk (60% loss). Although some amino acids essential for human metabolism are not available from plant material, plant proteins offer considerable efficiency advantages. In terms of nitrogen losses, a vegetarian diet that includes milk and eggs is more efficient than a meat protein-based diet.

24.2.3 Land use and urbanization

Land use determines the activities that result in losses of nitrogen to the environment. In principle, multiple land use (i.e., using the same piece of land for more than one purpose) is possible. Examples are the use of forest land for recreation and timber production, or of water bodies for fishing and water supply. However, in some cases, multiple use is excluded. For example, carbon sequestration cannot usually take place in the same area as intensive agriculture; the same piece of land cannot be used for food production/grazing of livestock and biofuel plantations, and this leads to 'competition for land'. This competition needs to be recognized and can be used as a constraint in projections. Table 24.2 lists important categories of land use and their implications with regard to nitrogen.

Land use itself is influenced by a multitude of drivers. Parameters like population numbers, macroeconomic growth, urbanization, globalization, resources (biodiversity, energy, water, soil and air) determine how people use the land, how it is managed, and in consequence how this relates to N. For instance, the global increase in population density from 2.2 persons per ha of agricultural area in 1960 to 4.1 in 2006 increased urbanization, agricultural intensity and fertilizer application (Erisman *et al.*, 2008). Moreover, higher meat consumption necessarily means an increase in the production of animal feed, resulting in changing land use and N cycles. Both factors are of higher importance globally than for Europe. Most recently, biofuel production has been recognized as an important parameter for change in land use and N-cycling (Erisman *et al.*, 2010; Howarth *et al.*, 2009).

Several studies have been conducted to determine how much land will be available for agriculture and bioenergy production, and how much for other purposes (Fischer *et al.*, 2010b; Lysen *et al.*, 2008; Londo *et al.*, 2010). Such data are important for estimating N losses, storage, and recycling. Figure 24.2 presents results obtained from the REFUEL project (Londo *et al.*, 2010; Fischer *et al.*, 2010a).

The increase in urban area resulting from urbanization (larger number of people in large cities) and urban sprawl (increased area requirement per urban inhabitant) compete against other land uses and affect the nitrogen cycle in various ways. As many human activities are focused in cities, cities will generate a considerable share of anthropogenic pollution (see Svirejeva-Hopkins *et al.*, 2011, Chapter 12, this volume).

City systems can evolve as a result of population growth, by increasing in either size (occupied land) or complexity (density). Each type of evolution has its own implications for what type of pollution dominates and for the fluxes of reactive nitrogen as they affect transport, heating/cooling requirements, or soil interactions. Modeling population density distributions (Svirejeva-Hopkins and Schellnhuber, 2008) helps potential trends to be understood. Total city areas to 2050 will have grown by only a few percent compared to the current city areas; especially affected will be cities with a population of 1–2 million (Svirejeva-Hopkins *et al.*, 2011, Chapter 12, this volume). Significant differences remain between different parts of Europe, especially regarding size (larger in Western Europe) and core densities (significantly higher in Eastern Europe). The most important changes with regard to nitrogen should be expected from changes in the extent of built-up area and associated urban sprawl (see Fischer *et al.*, 2010b).

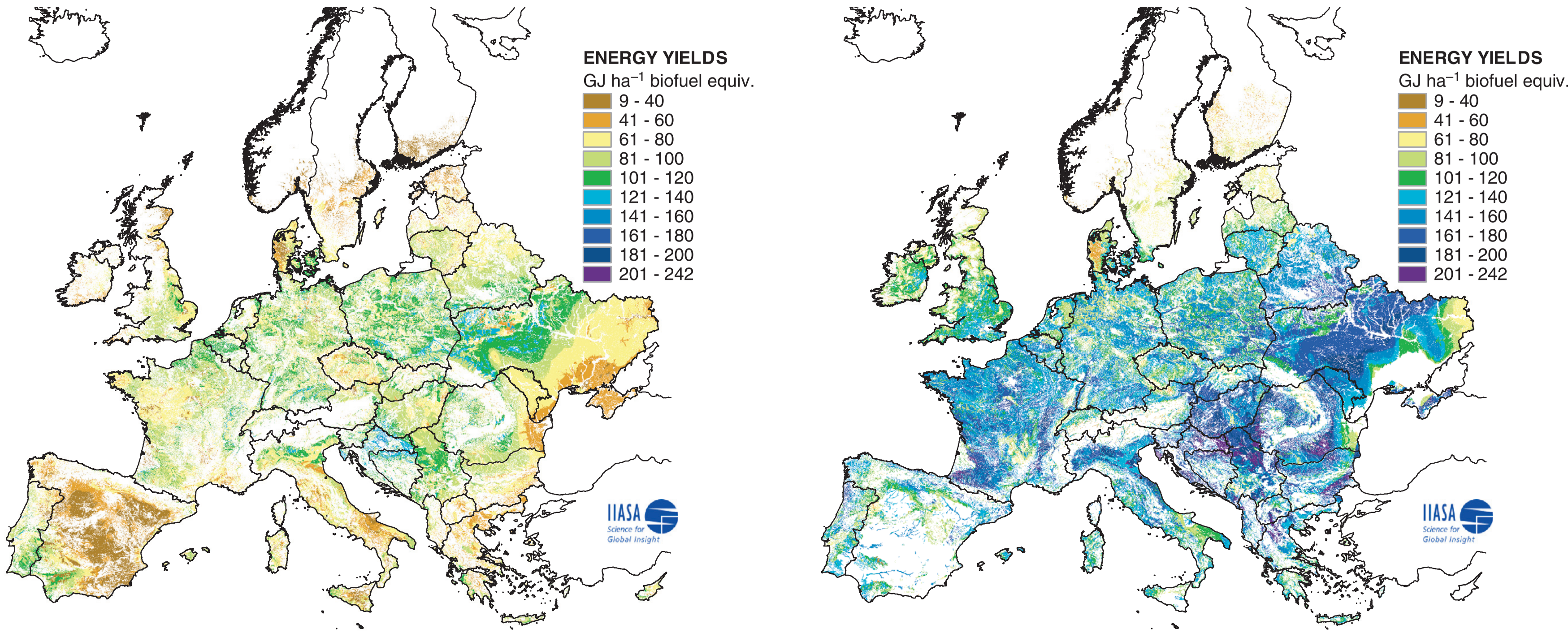

Figure 24.2 Yield expectations for specific crops (here: energy crops). Left panel shows the attainable energy yields for first- generation biofuels (starch crops, sugar crops and oil crops), right panel for second-generation biofuels (woody and herbaceous lignocellulosic feedstocks). Data from the EU REFUEL project, www.refuel.eu (Fischer *et al.*, 2010a, reprinted from Biomass and Bioenergy, with permission from Elsevier).

Urban areas are particularly relevant in terms of assessing population exposure to pollution. As urban areas are both emission hotspots and areas of high population density, a considerable part of the overall exposure depends on urban development. Larger population densities at typically higher pollution levels appear in urban areas of Eastern Europe. Scenarios on human exposure need to include consideration of spatially diverse pollution as well as respective population density.

24.2.4 Fertilizer application

The application of mineral fertilizer or manure to fields represents a direct release of N into the environment. While, under ideal situations, a crop can access a high proportion of the available nutrients, in certain circumstances nutrient dispersion to the environment cannot be fully constrained. OECD (2008) data show that the fraction of nitrogen captured in crops increased between 1990–1992 and 2002–2004 from 51% to 59% for the EU (year 2000 borders). Factors influencing nitrogen application range from energy prices (affecting also fertilizer prices) and crop prices to policy (adoption of nutrient management plans).

As the amount of agricultural produce is determined by demand, the extent to which soil nitrogen needs to be replenished by fertilizer is similarly affected. For its members, the European Fertilizer Manufacturers Association (EFMA) develops a fertilizer use projection, which is also made available to the policy process (EFMA, 2007). This work is based on the development of scenarios for crop demand and the respective fertilizer application rate as a top-down activity starting from the total EU (EU scenario) broken down to countries. The information is then complemented by detailed national information collected by designated EFMA national experts. The national dataset contains information on national agricultural and environmental policy, specific national/regional limitations or programs, and information from agriculture-specific media. National information is used to feed back to the European level in terms of nutrient demand. Data collection applies a time perspective of up to 10 years into the future. For 2017 a slight increase in mineral fertilizer use of 3.6% to 11 Tg N is expected in the EU27; increases will mainly affect new EU member states. EFMA not only uses this data as guidance for manufacturers but also exchanges and discusses results with a number of European and global agencies and institutions to further increase the robustness of the data.

These estimates take into account, but do not include, nutrients from manure application, which provides roughly two-thirds of N from mineral fertilizer (Leip *et al.*, 2011, Chapter 16, this volume). Future application of manure is usually estimated from the total nitrogen excretion of farm animals, whose numbers are determined by human population numbers and diet choices.

24.2.5 Reactive nitrogen in combustion and industry

Ammonia from the Haber–Bosch process is the starting point for production of the N used in most industrial processes (Domene and Ayres, 2001). Ammonium salts such as ammonium chloride and ammonium sulfate are used mainly as fertilizers. Nitric acid and nitro chemicals are used in the making of dyes, rubber, herbicides, pesticides, plastics like urethanes, and explosives like nitroglycerine and TNT. Urea is mainly used as a fertilizer and as a component of animal feed, but it is also used in resins like melamine, a thermosetting plastic used in laminates, cooking utensils, electrical appliances, and insulators. Hydrogen cyanide and its derivatives are used to make nylon, thermosetting plastic resins, synthetic rubber resins, acrylic fibers, and epoxy resins. Further products include dyes and drugs. The industrial uses of N continue to expand.

Recent global trends in the industrial uses of N are important for determining a mass balance of N, also because the uses of industrial N are growing. The total worldwide demand is expected to increase from 125 Tg N in 2007 to 142 Tg N in 2013 (IFA-PITCom, 2009). Global industrial (non-fertilizer) demand is projected to increase from 23 Tg N in 2007 to 28 Tg N in 2013, underscoring the importance of understanding the uses of industrial N. About 4.5 Tg of industrial N will be used in Western Europe in 2009, 0.7 Tg N in Central Europe, and 1.5 Tg N in the East Europe and Central Asia region, totalling about 6.7 Tg N for industrial processes in Europe. It should be noted that industrial N uses will account for a growing share of total N demand in Europe. In 2007 industrial N usages accounted for 30% of all N consumed in Western and Central Europe. This share is projected to expand to 34% in 2013 (Prud'homme, 2009).

The fate of the N used in industrial processes is not well understood. As more industrial uses for N are discovered, its importance and prevalence continue to grow worldwide. Mass balances for industrial N uses, however, are deficient because of the limited data available and the lack of powerful process simulation tools (Domene and Ayres, 2001). Additional life-cycle analysis of N use in industry is needed to better understand its contribution to N emissions and its ultimate fate in the environment. Only on such a basis the parameters describing changes in N use in industrial processes over time can be assessed.

Reactive nitrogen compounds are also created as by-products of combustion. Formation of NO_x, a common combustion by-product, depends on the N content of fuel and on combustion temperatures. The high temperature processes that create reactive nitrogen compounds are found primarily in power plants for electricity generation and industrial use, and internal combustion engines in the transport sector. Global formation of reactive nitrogen over this pathway has been estimated at 13% of anthropogenically created reactive N (Galloway *et al.*, 2008) immediately released to the environment. For Europe, excluding Russia, a similar share has been estimated (3.3 Tg NO_x-N or 13% of the 25 Tg N total: van Egmond *et al.*, 2002; 5 Tg industrial N production were also considered in estimating the total), but is expected to be somewhat larger for the EU27 (3.7 Tg NO_x-N or 17% of the 21 Tg total: Leip *et al.*, 2011, chapter 16, this volume). Differences in European figures, especially regarding the larger NO_x emissions from the smaller group of countries, also derive from different base years. More energy-efficient (high temperature) installations, a higher share of diesel cars, and transport expansion in general are drivers of a notable increase in NO_x emissions. For all these sources, abatement technology has become available and is being applied successfully, such that future emissions are expected to decrease despite increased activity (see Section 24.6).

24.2.6 Nitrogen and international trade

The demand for nitrogen products derived from population and dietary trends, energy production, and industrial products can be satisfied by production within Europe as much as by imports. Moreover, Europe exports goods containing nitrogen and also goods whose production chain requires nitrogen but contain no nitrogen themselves. Understanding trade and its function in replacing or enhancing European production may become very important in terms of assessing its nitrogen-related impacts on the environment.

Global trade, especially of agricultural goods, is strongly related not only to economic but also political conditions. Trade in the global nitrogen market is considerable already under present conditions (Galloway *et al.*, 2008). Trade is expected to be further liberalized, which will affect its quality and extent in the future. As trade liberalization may also affect critical infrastructure, a considerable amount of work has been done to understand the future situation (see e.g., the status of the Global Trade Analysis Project (GTAP, 2010). GTAP also liaises with IPCC work).

24.3 Effect orientation

24.3.1 Basic concepts

Oxidized and reduced nitrogen compounds transported through the atmosphere cause a broad sweep of adverse effects (the 'Key societal threats of nitrogen' described by the ENA). These effects inevitably give rise to remediation efforts. An effect-oriented scenario starts from an expected or desired future situation (target), which keeps adverse effects to an acceptable limit. Interpolation and/or expectations on economic and technological development may serve to identify the pathway to this expected future ('backcasting').

Effect orientation is important, as it is an independent approach complementary to driver orientation. It assumes policy responses to resolve adverse effects. If the action of a driver has been underestimated, environmental policy will have to react with even stricter abatement measures to achieve environmental targets.

A critical element in developing effect-oriented approaches is the setting of targets that are likely kept in the distant future (e.g. as mentioned above, human health). The targets need to be established such that an adverse effect that is known now – and will be considered sufficiently adverse and important to be maintained in the future – can be remedied. In the sections below we present targets that we consider to be stable even over long time periods and thus to be amenable to consistent environmental policy interventions.

Furthermore, as a part of scenario development, some concept regarding feasibility is needed. This requires the release (emissions) of environmentally relevant compounds first to be identified, and then for these emissions to be coupled to the adverse effects they cause. Such a task can be performed using models that capture the entire cycle between release and impact of compounds – see Figure 24.1 and De Vries *et al.* (2011, Chapter 15, this volume) for more information about 'integrated assessment models'. Specific technology measures need to be identified that are actually able to achieve the abatement required. Finally, when investigating interrelated environmental effects that are typical for nitrogen, cross-influences also need to be considered. Environmental policies and abatement technologies that address nitrogen should not be looked at in isolation (Oenema *et al.*, 2011, Chapter 4, this volume).

In the practical development of effect-based scenarios, it is quite common for a set target not to be fully achieved, even where policy development timescales are long. The basic concept of including abatement can, however, continue to be maintained; in this case, the limiting factor is not the target but rather the extent of available (known) technical measures for reduction. Terms used to describe such scenarios are 'environmentally considerate' or, more specifically, 'maximum feasible reduction'.

In addition to setting the conditions at a given point in time, some scenarios also attempt to provide the pathway leading to such a target. This procedure, starting from an effect-based target towards the current situation, is usually called backcasting (Carlsson-Kanyama *et al.*, 2008).

24.3.2 Setting targets for future development

Targets set for scenarios need to remain stable over the timescale of the scenario (see Table 24.3 for targets related to nitrogen). Obviously, targets for human health are the most easy to define and maintain, as human health is generally regarded as having a high value, a status which it will plausibly retain in the long term. This includes any direct nitrogen-based effects on human health.

Further risks to human wellbeing that are indirectly related to nitrogen are becoming increasingly important, partly because of improvements in scientific knowledge. Several of these indirect risks affect biodiversity and interact with other environmental issues. The WHO prepared a report as a contribution to the Millennium Ecosystem Assessment on the issue of ecosystems and human wellbeing (Corvalan *et al.*, 2005). Following the concepts of the Millennium Ecosystem Assessment, a first inventory of the effect of nitrogen on ecosystems services in Europe was produced (see Appendix C of Hettelingh *et al.*, 2008).

Ecosystem services describe the benefits to human wellbeing delivered by functioning ecosystems. The ability of ecosystems to perform such services can also be used as a robust target. We may specifically differentiate subtypes of ecosystem services. Provisioning services refer to ecosystems that help provide food, fiber, and fuel to humans. Regulating services refer to the potential of ecosystems to maintain the quality of air, water, or soil, and also the climate. Cultural services relate to recreational and aesthetic aspects of

Table 24.3 Quantifiable targets to avoid environmental deterioration due to nitrogen

Environmental problem	Nitrogen connection	Target
Loss of ecosystems services due to: • acidification • eutrophication • biodiversity loss	Atmospheric deposition of nitrate and/or ammonia	Critical loads (exceedance of soil specific values)
Adverse impact on plant species composition	Atmospheric concentration of ammonia	Critical levels (exceedance of critical NH_3 concentrations)
Crop damage	O_3 formation (NO_x chemistry)	Accumulated exposure over threshold (AOT)
Human health	NO_x concentration O_3 formation (NO_x chemistry) PM formation (NO_x chemistry and ammonia) Nitrates in drinking water	Years of life lost (YOLLs) Disablement Adjusted Life Years (DALYs) Quality standard (concentrations)
Climate change	N_2O emissions CO_2 emissions/uptake, as the natural C cycle is influenced by N in the environment O_3 formation (NO_x chemistry)	Global mean temperature (limit: 2 °C increase above pre-industrial)

ecosystems. 'Critical loads' describe a threshold of pollution beyond which the functioning of ecosystem services may be compromised.

An important tool for addressing future targets is dynamic modeling of geochemical and biological processes that drive changes in vegetation (De Vries *et al.*, 2010a). Dynamic modeling is especially important, as it is something of a tall order to avoid critical load exceedance. When the critical load targets cannot be met, dynamic modeling can be used in the context of integrated assessment to analyze the consequences for soil chemistry and vegetation in the future (see e.g. Posch *et al.*, 2008). Thus, effects-based targets can serve as ex post constraints of driver-based scenarios.

24.3.3 Critical loads for eutrophication – sample application

The critical load for eutrophication is the maximum allowable input of nitrogen below which adverse effects to the structure and functioning of natural ecosystems do not occur, according to current knowledge. According to current computations, the percentage of the European natural area at risk of eutrophication in 2000 was 77% (as demonstrated by Dise *et al.*, 2011, Chapter 20 this volume). Driver-oriented scenario analyses (Hettelingh *et al.*, 2008) show that current policies (current legislation – CLE) would reduce the area exposed to risk to 67% of the natural area in 2020. This percentage could be further reduced to 31% if the best available control technology (maximum feasible reduction – MFR) were applied in the agriculture and energy combustion sector to reduce emissions of ammonia and nitrogen oxides. While MFR is still not able to remove all risks, it comes closest to an effect-based approach that would be able to do so. Figure 24.3 illustrates how these policies affect the magnitude of critical load exceedance and the areas at risk of eutrophication in 2020. Hotspots of exceedance are the border between the Netherlands and Germany as well as Belgium, north-western France, and the Po Valley in Italy. All these hotspots show significant improvements with the application of appropriate measures.

24.3.4 Abatement costs

If we expect the environmental effects to determine the future release of nitrogen, then we must also expect to initiate specific abatement measures and accept to bear the costs. Integrated assessment models help prioritize measures so that cost-efficient remedies can be implemented.

Many of the ecosystem service functions outlined above may also be considered in terms of their financial benefits. Comparing these benefits with the costs of remediation measures may be an efficient way of formulating agricultural policies on the management of the nitrogen cycle. Welfare optimization (see Brink *et al.*, 2011, Chapter 22 this volume) is one modeling approach to provide maximum benefit to society and also to demonstrate that the cost of measures is turned into a net value for a community.

In principle, considering the negative effects on the environment (and their cleanup costs) will make it easier to justify abatement costs. In view of today's problems with N in the environment and the current exceedance of thresholds, from an effect perspective, it can be argued that a further increase in N exposure in Europe over large areas should not be expected, as long as environmental benefits maintain their high value in the eyes of the public.

24.4 Short- and medium-term scenarios

24.4.1 Timescale for scenarios

Both driver-based and effect-based approaches are used to develop scenarios. For emissions of air pollutants, agricultural and industrial production, land use and nitrogen inputs like

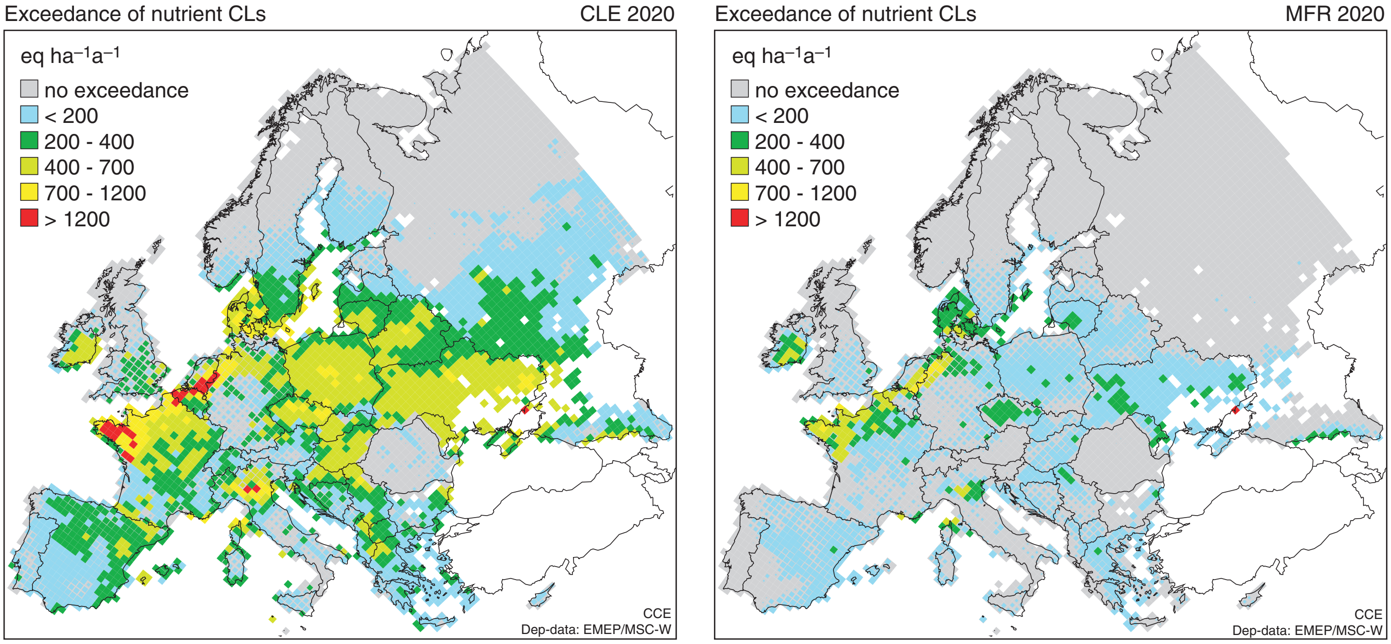

Figure 24.3 Exceedance of critical loads for eutrophication expected in 2020. The map on the left presents a driver-based projection of national emissions based on 'Current Legislation'; at the right the results of an effect oriented approach is shown, assuming Maximum Feasible Reductions as an option of getting closest to the target of no exceedance (source: Hettelingh *et al.*, 2008).

fertilizers, scenarios are often limited to 2020, and have only recently started to be extended to 2030. For this time period, any emission abatement technology implemented is expected to be already available, at least at an experimental stage. Projections thus need not consider new unknown technologies. The time horizon of 10–20 years is considered short-term.

Moreover, the most recent agricultural projection of the Food and Agriculture Organization of the United Nations (FAO, 2003) covers the period 2000–2030; a more recent outlook for 2050 is available, although with less geographic detail than the 2030 projection. Agricultural systems will show dramatic changes in these five decades, according to FAO. The changes are related to various developments, including population, changing markets and trade, technology, and diets. In scenarios for analyzing the acceleration of the nitrogen cycle, agricultural developments are the major drivers.

There is a need to go beyond this scale. Most scenarios constructed for analysis of drivers of climate change consider a 100-year time period. To exhibit the potential co-benefits of expected measures with respect to air pollution, air pollutants have also started to be looked into. A recent workshop organized under the UNECE Convention on Long-range Transboundary Air Pollution ('Workshop on non-binding aspirational targets for air pollution for the year 2050' held in Utrecht, March 2009) called for an extension to 2050. This 40-year timescale will be covered in medium-term scenarios.

The IPCC 'Second Report on Emission Scenarios' (SRES: Nakicenovic *et al.*, 2000) for projecting CO_2 emissions uses consistent storylines to illustrate possible future situations. The scenarios of the Millennium Ecosystem Assessment (MA, 2005) were built based on the SRES concepts. For the Millennium Ecosystem Assessment, information on nitrogen does play an important role, and nitrate leaching and transport in watersheds is also covered. Because of large uncertainties in non-energy-related fields the temporal extension is limited to 2050. Scientific evaluation is still going on, and important results have recently been published (Bouwman *et al.*, 2009; Van Drecht *et al.* 2009; Seitzinger *et al.,* 2010).

Any scenario beyond the year 2050 is then considered a long-term scenario. Such scenarios typically are being prepared in the context of climate change considerations. Important examples of scenarios are presented in Table 24.4. Sets of scenarios contain elements of both driver and effect orientation.

24.4.2 Basic approach – Short-term scenarios

Over a timescale of 10–20 years, a generally good understanding of the systematic relationship and interaction between economic development and environmental effects can be expected. Thus for short-term scenarios it is useful to prepare a 'baseline' path of development, which covers the most probable expectations at the time of inception of the scenario. This is based on a consistent set of assumptions used in a similar manner for different applications. Typically, any foreseen future changes are already considered. This includes, for example, emission abatement legislation already in place but effective in the future (scenario 'with measures'). Despite the fact that such a path may need to be adapted to a changing reality (e.g. economic/technological development), relying on a single scenario is advantageous for comparing both measures and consequences.

To understand the system response to certain, fixed interventions, the 'baseline' scenarios are often extended by certain, given measures (scenario 'with additional measures') which are not yet part of mainstream expectation (legislation or regulation). It is the common understanding that, even if development

Table 24.4 Overview on important scenario activities related to the future release of nitrogen to the European environment. See text for more detailed description

Activity	Reference	Remark/description
European Consortium for Modelling of Air Pollution and Climate Strategies EC4MACS[1]	EC4MACS (2010)	Short term: 'current legislation' vs. 'maximum reduction' approach, limited to the atmosphere as carrier.
IPCC second report on emission scenarios SRES[2]	Nakicenovic *et al.* (2000)	Long term: four main storylines. Limited to energy and the carbon cycle
Millennium ecosystem assessment[3]	MA (2005)	Medium term, four storylines similar to SRES; extends to nitrogen, covers water and ecosystems
Eururalis	Eururalis (2010) Rienks (2008)	Short term, focus on land use, agriculture and related activities; an activity on mid-term scenarios is under way; four storylines
OECD environmental outlook	Bakkes *et al.* (2008)	Short-term perspective, many results extended to medium term; covers air, water pollution and agriculture; scenarios are driver-oriented vs. climate- (effect-) oriented
Representative Concentration Pathways (RCP)	Representative Concentration Pathways (2010)	Long-term, with an ambition to 2300; extends SRES to more compounds (including nitrogen compounds), but excludes water, ecosystems

(1) This scenario approach has been used for European air quality policy and is reflected in ENA by Moldanová *et al.* (2011, Chapter 18, this volume) and Butterbach-Bahl *et al.* (2011, Chapter 19, this volume).

(2) Emission scenarios have been used as input to climate models for climate projections; the impact of climate change on aspects of the nitrogen "key threats" is investigated by Grizzetti *et al.* (2011, Chapter 17, this volume) and by Butterbach-Bahl *et al.* (2011, Chapter 19, this volume).
(3) Used also by Grizzetti *et al.* (2011, Chapter 17, this volume).

does not follow the baseline projection, at least the difference between the baseline and the 'with additional measures' scenario will be maintained. This will be the case when all changes considered are merely incremental to the major drivers of change, and the majority of uncertainty in future development is due to these major drivers rather than to the increment.

The approach has been extensively applied in modeling European energy policy and the environmental applications derived from such energy models. Specifically, the PRIMES energy model works on that basis, providing a baseline of energy consumption and some industrial activities. These results are used as input by the GAINS model (http:www.gains.iiasa.ac.at) which links it to emission abatement measures, their abatement potential and applicability, and their costs, as well as to environmental effects.

Coupling of PRIMES and GAINS is one essential part of the EC4MACS project (European Consortium for Modelling of Air Pollution and Climate Change, EC4MACS, 2010). This project prepares and provides consistent scenarios on energy demand/consumption, agricultural production, and emission abatement measures directed toward reducing air pollution and greenhouse gas emissions, and their costs. In this modeling chain, the CAPRI agricultural model is also of considerable interest to the nitrogen cycle, as it models the agricultural production supply as a result of demand and policy interventions. EC4MACS covers the EU member countries, but supplementary data are provided in GAINS to cover the whole of Europe.

In this chapter, we will use results of EC4MACS scenarios to illustrate nitrogen pathways in the short term. We will focus on the C&E package, which reflects the Climate and Energy package adopted by the European Commission.

24.4.3 Basic approach – medium-term scenarios

Some of the simplifications applicable to the short-term scenarios will no longer be plausible with respect to the 2050 timescale. For 'medium-term' scenarios there will be a need to account for substantial technological change beyond what currently exists as pilot plants. The idea of introducing 'storylines', originally developed for climate research (Nakicenovic *et al.*, 2000), allows several strands of activities to be consistently tracked into the future, based on the scopes of matching parameters. Scenarios have been grouped along two sets of key antagonisms (convergent world versus heterogeneous world; highly material intensive versus sustainable, service- and information-oriented economy), yielding four 'families' of scenarios. Even this concept is not only based on drivers; it also considers the effect-based approach in the 'sustainable economy' type of scenarios which aim to maintain environmental quality.

This idea has been used widely. In addition to its integration into the Millennium Ecosystem Assessment (see above), it has been applied in connection with nitrogen pollution in Europe in the Eururalis project (Rienks, 2008; see also Verburg *et al.*, 2006, for more information on land use scenarios).

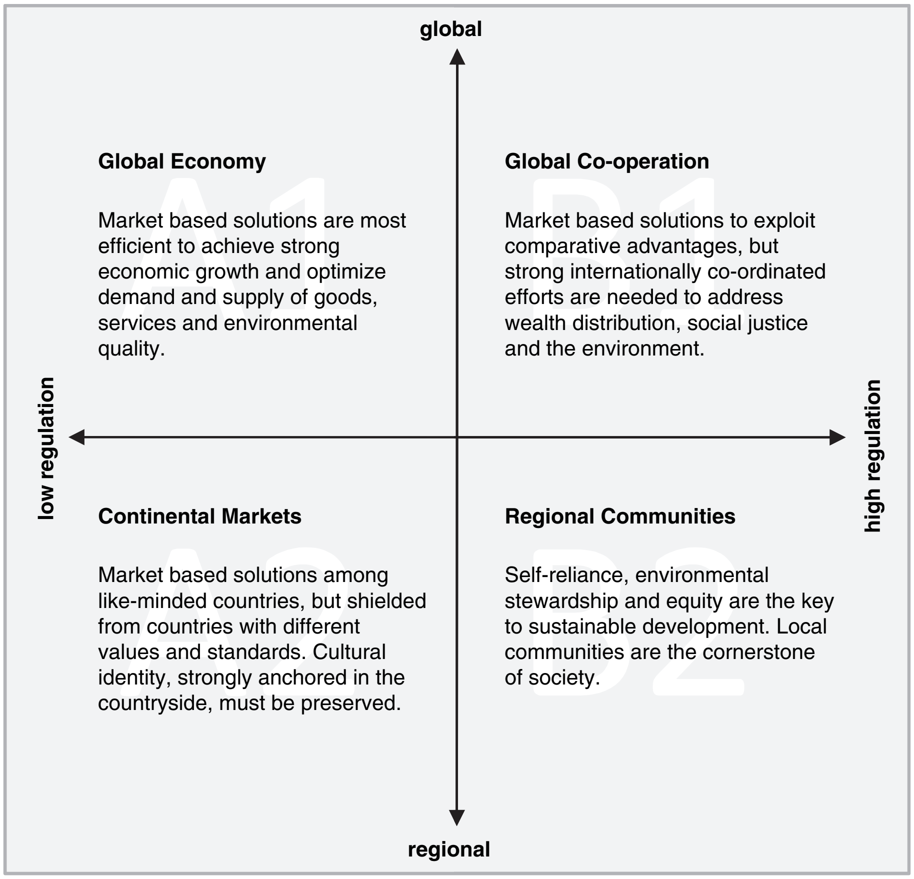

Figure 24.4 The four Eururalis scenarios, based on the concept of the IPCC SRES scenarios.

Some results will be shown in Section 24.6. An overview of the Eururalis definition of storylines is presented in Figure 24.4. Again, these storylines are being built up from pairs of opposing parameters.

Eururalis scenarios in combination with the IMAGE model provide detailed information on the agricultural sector, including changes in livestock, N fertilizer use, and land cover. Use of integrated models such as INTEGRATOR (see below) allows assessment of the impact of those changes on N (NH_3, N_2O, and NO_x) emissions to the atmosphere, and N (nitrate and ammonium) leaching to groundwater and surface water. As this model does not include other anthropogenic emissions, only a very small part of NO_x emissions to the atmosphere (emissions from soil) is considered. In Eururalis, the remaining NO_x emissions from combustion processes can be taken from the IMAGE model on a coarser scale. While scenarios currently go to the year 2030, Eururalis works on an extension to 2050.

Here we select scenarios A1 (Global Economy) and B2 (Regional Communities) to highlight the extremes of future possibilities: full globalization with a focus on economic growth versus regional protection with a focus on local cultural values.

The Eururalis scenarios have also been chosen to represent the future situation in the NitroEurope integrated project (NEU, 2010, Sutton *et al.*, 2007) and are processed using the dynamic nitrogen flow model INTEGRATOR (De Vries *et al.*, 2010b). An important aspect of Eururalis is that within the scenarios different policy options can be evaluated. The interference of different policy options–combinations of several individual measures – and other driving forces can be assessed. The following policy options relevant in the EU have been considered in INTEGRATOR.

- Policy on the Common Agricultural Policy (will affect both land use and livestock numbers and allocation).
- Policy to stimulate the use of bio-energy (will affect land use).
- Policy on Less Favoured Areas (will affect land use).

24.5 Developments toward long-term scenarios

24.5.1 Approach

Extending a scenario beyond 2050 requires either a highly aggregated approach to be taken or the storylines to be defined in greater detail. Erisman *et al.* (2008) use a highly aggregated approach to estimate the global release of nitrogen to the environment based on the SRES storylines up to 2100. The authors do not distinguish N species, regions, or release conditions, and base their estimates on just five driving assumptions (size of population, food quality, food equity, efficiency gains and biofuel production). To obtain more specific projections, considerably more detail is required.

This detail needs to be derived on a technology level. Any ideas on such future technologies must necessarily be speculative – projecting how the technologies of 2100 (90 years hence) will look is like predicting the current situation from the perspective of 1920. At that time fossil fuels were in use, ammonia production from the elements had been invented, but the implication of each of these technologies, or the changes they would bring in terms of everyday life all over the globe could not be foreseen.

We will now look at individual 'emerging issues' to describe possible future developments toward 2100, focusing especially on those that have not been already discussed as drivers. We will try as much as possible to link these issues with information available from other sources so as to draw plausible conclusions on the overall implications of these developments. A quantification of these implications has rarely been presented, and thus only few quantitative analyses can be provided.

24.5.2 Emerging agricultural systems

Improvements in agricultural systems beyond 2050 may range from (1) increases in the efficiency of nitrogen uptake of moderately changed systems to (2) nitrogen emission reductions due to drastic changes in agricultural technology.

Uptake efficiencies may be increased by improving (1) the spatial distribution of fertilizer via precision agriculture placing nitrogen at optimal distances from seeds or root zones with rates adjusted to current soil and crop conditions (Pagola *et al.*, 2009) and (2) the timing of fertilization via controlled-release fertilizers (Chen *et al.*, 2008; Yu *et al.*, 2006) and application splitting (Olfs *et al.*, 2005). Such improvements to current systems are to some extent already available, although not widely implemented.

Drastic changes in agricultural technology are more difficult to predict, but several general arguments can be made. First, agricultural commodities may be produced in a more controlled environment in the future. Such systems could include soilless (hydroponic) agricultural systems (Jensen, 1997) in a closed environment with possibly zero nitrogen emissions. Second, future machinery for soil-based agriculture is likely to be more receptive and responsive to physical and biochemical signals and more versatile. The likely state of the art of such machinery would greatly depend on general progress in artificial intelligence (Murase, 2000). Agricultural robotic tools could be used for all agricultural management tasks including weed and pest control (Slaughter *et al.*, 2008), irrigation (Phene, 1989), harvesting (Tanigaki *et al.*, 2008; Van Henten *et al.*, 2009) and determination of soil properties (Hemmat and Adamchuk, 2008; Liu *et al.*, 2008). Robotic tools may also permit the use of multiple crop and companion planting systems as opposed to the crop rotation systems currently used with a single crop per field. Such systems may increase overall yields through decreased pest pressure and pesticide requirements and improved light, land, water, and nutrient efficiencies, as well as reducing soil erosion.

Agricultural nitrogen emissions in a robotic agricultural system could substantially decrease because of higher fertilizer use efficiencies and reduced fertilizer requirements, higher yields and lower harvest losses, and reduced losses of nitrogen from other sources (soil, fuel).

24.5.3 Cereal crops with N_2-fixing capacity

Cereal crops with N_2-fixing capacity have long been a dream of scientists. If N losses from soil–plant systems are to be eliminated, a regulated N supply through a plant fixing its own N_2 would be ideal (Ladha *et al.*, 2005). Two different ways of engineering cereal crops have been explored since the early 1980s and again in the late 1990s (Giller and Merckx, 2003). The first approach is the introduction of the enzyme nitrogenase into the cereal plant so that it can fix atmospheric N_2 directly. The unicellular cyanobacterium *Gloeothece* synthesizes nitrogenase in the dark and can fix atmospheric N_2 when returned to the light. It has been proposed to engineer this ability into plants. However, such a plant system must supply energy for nitrogenase synthesis during the night and ensure protection of nitrogenase from molecular oxygen during photosynthesis in the daytime (Giller, 2001). Lack of funding for this research means that there has been little advance since the early 1980s. An alternative may be oxygen-tolerant nitrogenase. However, irrespective of the approach used, the functioning of nitrogenase will require the supply of reductant and electrons, and this may be much more problematic than engineering plants to generate nitrogenase.

The second approach is to manipulate the cereal plant so that it can nodulate with rhizobia, bacteria that live in symbiosis with the plant and that can fix atmospheric N_2 in exchange for energy delivered by the plant. Although some exciting progress has been made with rice, the prospect of N_2-fixing cereal crops remains distant (Ladha and Reddy, 2003).

There are also disadvantages. Crop yields may be lower, as part of the energy from photosynthesis has to be invested in the process of breaking the triple bond of the N_2 molecule. This energy cost may be 33% of plant photosynthate (Minchin *et al.*, 1981). If we assume that crop yields would be 30% lower than the current European mean of ~3400 kg per hectare for the ~120 million hectares of harvested cereal area (FAO, 2009), an additional 35 million hectares would be needed to achieve the same total production. Although energy costs of N_2 fixation are high, they may not be higher than those of nitrate assimilation (Pate and Layzell, 1981). It is thus uncertain what the net impact of the N_2-fixation process on yields would be.

A further disadvantage of N_2-fixing nonlegumes is their high phosphorus requirement compared to crops that do not fix N_2 (Giller, 2001). Large-scale production of N_2-fixing cereals would thus accelerate the depletion of global phosphate-rock resources (Cordell *et al.*, 2009).

24.5.4 Collection and recycling of human excreta in agriculture.

While fertilizer nitrogen can be created from the atmosphere, this is not the case for phosphate. Depletion of global rock phosphate reserves is expected to become critical in the coming five to ten decades (Herring and Fantel, 1993). This will possibly lead to price increases for phosphate fertilizers, with important consequences for agricultural production systems beyond the time horizon of 2050.

Table 24.5 Meat/egg production and consumption, 2007, in the EU countries

Activity	Meat/egg production [10^6 ton/yr]	Share of domestic production	2007 diet [kg/cap/yr]	Healthy diet [kg/cap/yr]	Reduction in intake
Ruminants[a]	9.3	96%	19.8	6.24	68%
Pigs	22.9	108%	44.8	5.66	87%
Poultry	11.4	103%	23.1	25.3	32%
Eggs	7.0		14.1		
Total meat + eggs	50.6		101.8	37.2	63%

[a] Ruminants are cattle, sheep, and goats
Sources: FEFAC, 2008; healthy diet: Stehfest *et al.*, 2009

Considerable amounts of phosphorous are available in human excreta. As rock phosphate reserves decrease, this other source is likely to be tapped. Closure of the P cycle also contributes to nitrogen recycling, while currently both compounds are disposed of in wastewater treatment plants.

Both P and N are predominantly excreted in liquid form (urine). Sanitation systems for utilizing human excreta will likely provide separate collection for urine and feces. Magid *et al.* (2006) describe how such a sanitation system might look in practice. Different handling is suggested according to population density (e.g. urban centers versus rural areas). A decisive element in such a system is a strict separation of human excreta from industrial waste, as the latter may be contaminated with xenobiotic compounds. According to the authors, the additional costs of the alternative system would be fairly modest. Using Magid's estimate of N excretion in urine (4 kg per person and year) yields roughly 3 Tg for Europe, about one-quarter of the N amount currently applied as mineral fertilizer.

Although applying such systems would relieve the pressure to fix nitrogen from the atmosphere (and to mine for phosphate), this measure alone would not change conventional application practices. Despite closing the cycles, emission reductions would not occur in agriculture but in wastewater treatment and in industrial fertilizer production. The major release pathways of nitrogen into the environment would remain intact.

24.5.5 Effects of a low-meat scenario on nitrogen emissions

It is well known that the quantity and quality of the human diet has an impact on the environment. Preventing food wastage and overconsumption of food automatically decreases the amount of food necessary to feed the entire global population. The actual composition of the human diet is also relevant because of the different environmental footprint of its components. Carlsson-Kanyama and González (2009) compared three meal options from Sweden each with an edible weight of about 0.5 kg. The meals had similar energy and protein contents but the greenhouse gas emissions varied from 0.42 (soybeans) through 1.3 (pork meat) to 4.7 (beef) kg CO_2 equivalents.

In a Dutch study, four low-meat diets were compared with respect to their effect on global greenhouse gas emissions (Stehfest *et al.*, 2009). The diets ranged from (1) no animal products in the diet, (2) no meat, (3) no ruminant meat to (4) a 'healthy diet'. The healthy diet is based on sparing consumption of ruminant meat and pork (Willett, 2001). The healthy diet has a daily intake of 10 g beef, 10 g pork, 46.6 g chicken meat and eggs, and 23.5 g fish per capita, based on which some calculations on the effect on nitrogen emissions have been made for the whole of the EU. There are no changes assumed in the milk consumption per capita. Table 24.5 presents some data on actual meat production for the total EU (FEFAC, 2008). Using annual meat production and shares of domestic production we estimate the average intake of meat products and eggs per capita in the EU and compare this to the consumption in the case of the healthy diet. The total potential reduction in meat and egg consumption is 63%. As the milk demand is kept stable, there is also no reduction in the number of dairy cattle and cattle for replacement. The number of beef cattle, pigs, and poultry can be reduced because of the decreased demand for their products. Simple calculations show that nitrogen excretion in the EU could decrease by about 44% and the ammonia emissions by about 48%. The potential decrease in ammonia emissions is somewhat higher because the number of housed animals (which contribute more strongly to NH_3 emissions) decreases while the number of grazing animals remains constant. In essence, low-meat diets may result in lower greenhouse gas emissions and in lower ammonia emissions.

24.5.6 Biofuels and nitrogen in the environment

While the REFUEL project (Londo *et al.*, 2010; Fischer *et al.*, 2010a,b) focuses on bioenergy potential in Europe by 2030, it also provides relevant information for the longer time scales. According to their 'Land use-energy scenario', which we regard as the upper margin of potential, about 50 Mha cultivated land and 19 Mha pasture land could be made available for biofuels in a region covering the whole of the EU and Ukraine (plus Switzerland and Norway), while fully securing food production. This is a third of the region's cultivated land and about 20% of total pasture. Creation of new agricultural area is not

Table 24.6 Models contributing to the 'Representative Concentration Pathways'

	Model	Publication	Description
RCP8.5	MESSAGE	Riahi *et al.* (2007)	Rising radiative forcing to 8.5 W/m^2 in 2100
RCP6	AIM	Fujino *et al.* (2006)	Stabilization at 6 W/m^2
RCP4.5	MiniCAM	Clarke *et al.* (2007)	Stabilization at 4.5 W/m^2
RCP3-PD(2.6)	IMAGE	Van Vuuren *et al.* (2007)	Peak at 3 W/m^2 before 2100 and decline thereafter

assumed, partly because there is not much unused land in Europe. Diet changes, as described in the section above, are not considered and may even enhance this bioenergy potential.

In their reports, authors do not cover nitrogen requirements. As biofuel production adds to existing food/feed production, which will be intensified but not replaced, we may assume that the nitrogen requirements for food/feed production will in principle remain, save for some efficiency increases. Thus possible fertilizer needs for biofuels would occur on top of existing or expected needs for food/feed production, irrespective of the fact that the same area is used.

In contrast to food and feed production, which also aim to provide protein to animals and humans, organic nitrogen is an undesired component in biofuel crops. Second-generation biofuels can thus, in principle, be grown on relatively small amounts of fertilizers, or even without addition of nitrogen under certain circumstances (Tilman *et al.*, 2006). The other end of the scale, focusing on quick growth of biofuels without considering nitrogen demand, could easily require a fertilization rate of 100 kg N/ha, more closely resembling the current agricultural situation (but not nearly the level needed for first-generation biofuels). Using the land potentials of REFUEL, this would add about a third to the current fertilizer N input.

Depending on the assumptions made (and how practical implementation occurs) it is clear that biofuel production could become a marginal factor, or a major player, in future nitrogen load to the environment in the long term. An increase in nitrogen input to soils could easily translate to similar increases in emissions to the atmosphere and to watersheds.

24.5.7 Long-term greenhouse gas scenarios

Scenarios on future greenhouse gas emissions were initially limited to CO_2 (Nakicenovic *et al.*, 2000). As climate models have been further developed and are now also able to account for atmospheric chemistry and for the effects of tropospheric ozone or particulate matter, emission data must also be adapted accordingly. The first results of the ongoing work to create new IPCC scenarios have recently been made available. Data of the 'Representative Concentration Pathways' (RCPs) are hosted by among others IIASA (Representative Concentration Pathways, 2010). Through this site, more extensive documentation is available, although still in draft form, the 'RCP handshake document'.

The RCPs too consist of elements of both driver orientation and effect orientation. Here it is the respective pathways themselves that cover certain expectations on future abatement (radiative forcing target). The respective storylines leading to the individual RCP derive from relatively independent exercises. Table 24.6 shows that each of the storylines is represented by just one model.

Because of lack of knowledge regarding future technologies, a detailed accounting of abatement options is not possible. The storylines carry just a general understanding of long-term development, not only covering CO_2 but also including gases relevant for the N cycle (NH_3, NO_x, N_2O).

24.6 Available nitrogen scenarios for Europe

24.6.1 Concept

The concepts for creating scenarios and projections as described above have been consistently applied to specific situations in Europe. Here we provide a compilation of existing and publicly available estimates of nitrogen release. Certain limitations make it difficult to compare data, similar to comparing the current or the past situation.

- Depending on the purpose for which data have originally been collected, only some of the nitrogen release sources are covered in the respective studies.
- Likewise, some of the emission fluxes (pathway of reactive N) may be missing. Nitrogen release through the aqueous pathway (surface water and groundwater) is seldom dealt with in scenarios covering emissions to the air. Moreover, modeling of water pollution is mostly based on watersheds, while modeling of airborne pollution (and greenhouse gases) usually follows administrative boundaries.
- Because of the significant efforts on the part of the European Union to collect and evaluate environmentally relevant information, there are large differences in data availability between the EU member countries and the rest of Europe. While the EU comprises two-thirds of the total European population, it covers under half of its geographical area. While the EU does not represent Europe as a whole, it is often very useful to perform reliable comparisons on available information rather than attempt complete coverage.

In Figures 24.5–24.7, we present projections of nitrogen release to the atmosphere (and leaching to groundwater, in one case). The frameworks of the respective scenarios were introduced in the previous sections. Results from the GAINS model represent a short-term scenario, comparing current legislation and control options. The Eururalis scenarios, as

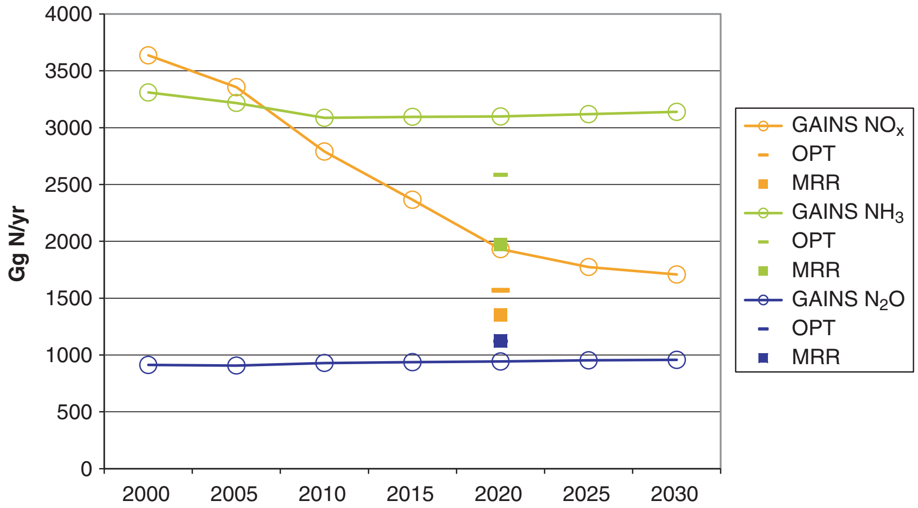

Figure 24.5 Total release of nitrogen compounds (NO_x, NH_3, and N_2O) to the atmosphere from EU27 from the GAINS model (scenario 'C&E package'; current legislation plus two levels of further action for the year 2020 only).

used by the INTEGRATOR model, represent a mid-term scenario interpreting the IPCC storylines, but nevertheless not extending beyond 2030 in the current phase of development. The RCP work reflects long-term climate scenarios. As all these approaches are work in progress, we can merely present results for the time of writing (end 2009). As generally the work focuses on elements other than nitrogen, further improvements seem possible and may be needed in order to understand the future role of nitrogen in the environment.

Further to the European projections presented, it seems useful to refer to the global scenarios published by Erisman *et al.* (2008). As mentioned before (Section 24.5), global totals of nitrogen release only are available from this study, based on the impacts of a few key drivers. Despite the diversity of storylines chosen, all scenarios point toward increased pollution, constrained by a factor of roughly two, mainly as a result of the still strongly increasing world population. In contrast, European population is expected to decrease (UN, 2004), which should also drive a decline in nitrogen pollution.

24.6.2 Short-term scenarios: GAINS

The results from GAINS (Figure 24.5; the model itself is accessible at GAINS, 2010) display important changes – reductions in NO_x emissions – already in the current legislation scenario. Still further reductions in NO_x emissions, and also considerable reductions in NH_3 emissions seem feasible should appropriate measures be taken. It is particularly interesting to note that applying additional measures leads to increases in the case of N_2O emissions. This is quite typical for nitrogen because of the effects of pollution swapping. The GAINS model scenario here aims to reduce emissions of air pollutants and ignores the adverse effects of N_2O emissions.

24.6.3 Medium-term scenarios: INTEGRATOR

The INTEGRATOR model was used in Eururalis to predict the N input and output fluxes of agricultural areas in response to the A1 and B2 default scenarios, as explained in Section 24.4. Here we present the results of the main N output fluxes (Figure 24.6) for the period 2000–2030 (see also De Vries *et al.*, 2011, Chapter 15 this volume, who describe developments since 1970). While this period is only short-term, here we treat it as an example of a medium-term scenario because of the methods it uses. Differences in N fluxes are fairly small between the two scenarios. The A1 scenario assumes much larger crop production than B2, while under A1 livestock production is only slightly higher. The A1 scenario also provides clearly higher N fertilizer use and plant uptake, which leads to about 10% higher gaseous emissions (N_2O, NO_x, NH_3), but only about a 7% increase in leaching compared to the more moderate B2 scenario. INTEGRATOR shows only half the N_2O emissions of GAINS (Figure 24.5), which is mainly because of the much higher indirect emissions included in GAINS (N_2O formation attributable to agricultural N release, but not occurring directly at the plot), namely, 45% of total emissions. In particular, indirect emissions from leached N are considered to be much smaller by INTEGRATOR because of a lower leaching fraction and a lower emission factor (see De Vries *et al.*, 2011, Chapter 15 this volume). Moreover, INTEGRATOR, unlike GAINS, does not consider NO_x emissions from combustion processes, which are responsible for the main share of emissions, as these come from non-agricultural sources. More information on the INTEGRATOR approach and the results obtained is given by De Vries *et al.* (2010b,c).

In general, the changes in the coming decades are expected to be smaller than those of the past (see De Vries *et al.*, 2011, Chapter 15 this volume), and the scenarios are also expected to differ less than those described in GAINS. While GAINS specifically focuses on abating emissions, in Eururalis the alternative scenario provides some elements of environmental consideration, but this is meant to be consistent rather than specifically targeted; this, in turn, could indicate that the maximum reductions outlined in GAINS are difficult to achieve, as they are not focused on being fully consistent. Moreover, Eururalis is not able to capture the decrease in NO_x emissions shown so clearly by GAINS, as it is limited to the agricultural system and does not cover combustion emissions and their reductions.

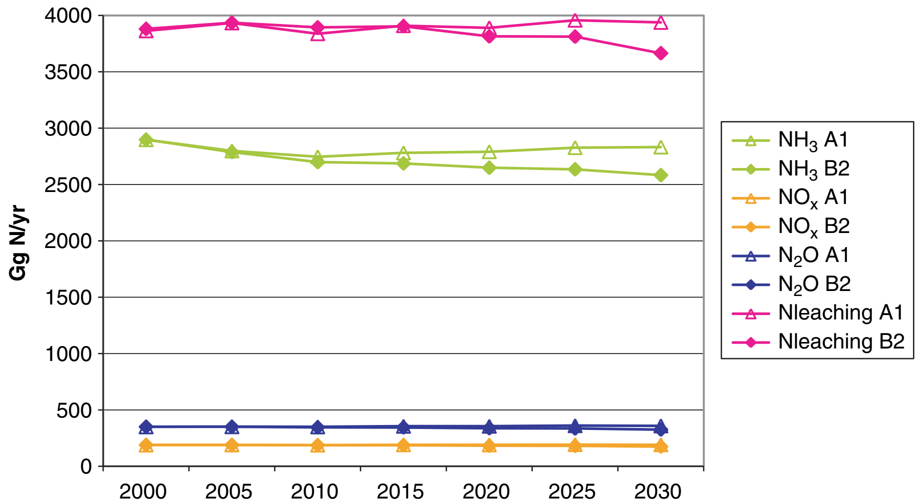

Figure 24.6 Release of nitrogen from agriculture and animal husbandry from EU27 according to the INTEGRATOR model using Eururalis (version 2.0) scenarios. A1 scenario stands for a global, low regulation scenario, B2 for a regional and highly regulated, environmentally considerate scenario. Note that only agricultural emissions are included, in contrast to other studies that provide a complete inventory of emissions from all sources.

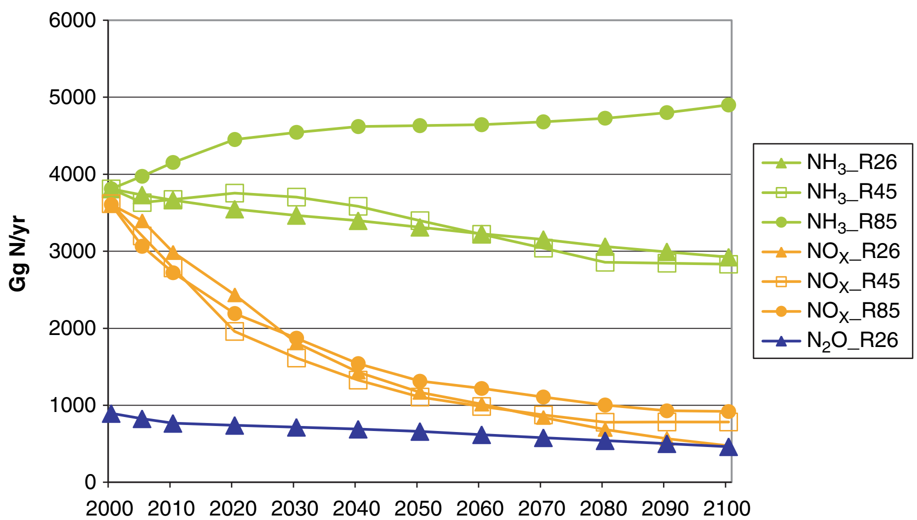

Figure 24.7 Nitrogen emissions from EU27 as of RCP (v.0.9.9rc11), for three different storylines on radiative forcing. Only the model running the R26 storyline (IMAGE) provides spatially distributed N_2O emissions. Storyline names indicate the radiative forcing exerted in 2100, between 2.6 and 8.5 W/m^2.

An estimation of the future development of nitrate in river discharges is available from the Millennium Ecosystem Assessment (Seitzinger *et al.*, 2010), while detailed data is also presented by Grizzetti *et al.* (2011, Chapter 17 this volume). The Millennium Ecosystem Assessment, whose concepts are very similar to those of Eururalis, provides a mid-term scenario based on an interpretation of the original IPCC storylines, and extends to 2050. The total release of nitrate from European catchments is estimated to change from 4.04 Tg N in 2000 to 3.99 Tg N in 2050 (or 3.5 Tg N, for an environmentally sensitive scenario), which is close to the agricultural N leaching reported just for the EU in the model results above (Figure 24.6). The slightly decreasing trend over time is also interesting. Data on the EU are not available and would not really be useful, as the flux into the marine environment is critical, especially with respect to the seas that have limited exchange with the world's oceans: the Baltic Sea, Black Sea, and Mediterranean.

24.6.4 Long-term scenarios: RCP

As the long-term greenhouse gas scenarios now also include the release of reactive trace constituents, it is useful to include them in this comparison. The RCP results (Figure 24.7), like GAINS, cover all anthropogenic release to the atmosphere. The results presented for the EU thus generally resemble those of GAINS. While NO_x declines strongly (and most clearly until 2040), ammonia and nitrous oxide emissions display an unclear trend. The most environmentally considerate storyline (R26) suggests that both nitrous oxide and ammonia will decrease consistently until 2100. This is because it was set up to keep greenhouse gas emissions to the minimum (which was not an aim in the GAINS scenarios used). Consequently, ammonia emissions are reduced much less in the RCPs than in the GAINS scenario optimized for maximum reduction.

24.6.5 Outlook

Even across different timescales, comparison of existing scenarios on future nitrogen emissions provides interesting insights that are a valuable basis for further work. In general, trends are comparable, with emissions of NO_x decreasing and N_2O and NH_3 largely remaining at a constant level over time. Where differences occur, these can be explained by recognizing the different ambition levels of the respective scenarios or simply by understanding the different system boundaries involved.

While scenarios are available that cover all media, there is not one single approach that consistently addresses nitrogen fluxes to the air, to groundwater, and to surface water. Scenarios have been built with respect to environmental problem areas, the key topics being ecosystem protection, air pollution, and greenhouse gas emissions. This is also true for the spatial resolution, with riverine pollution being defined along watersheds, air pollution according to country boundaries, and greenhouse gas emissions according to still larger units, possibly with some downscaling included. Extensions into the neighboring environmental media are being performed slowly. There may be some risk that storylines become inconsistent in the course of such an extension.

The efforts of Leip *et al.* (2011, Chapter 16 this volume) demonstrate how nitrogen budgets can be used to assess specific fluxes in more detail. In principle it should also be possible to provide the input data needed to derive such budgets for scenarios. Some effort will be needed to clearly define such a task. Specifically, a clear separation is required to assess the extent to which a specific storyline is affected by drivers only, and how strongly effects are considered. The extent to which effects are relevant may be called the ambition level. Covering nitrogen in different environments and media will need tradeoffs to be considered. Constraining the respective nitrogen flows in a budget approach will clearly improve the consistency of scenarios.

Acknowledgements

This chapter was prepared with the support of the NinE Programme of the European Science Foundation, the NitroEurope IP (funded by the European Commission), the COST Action 729 and the EC LIFE project EC4MACS.

References

Bakkes, J. A., Bosch, P. R. Bouwman, A. F. *et al.* (eds.), (2008). *Background report to the OECD Environmental Outlook to 2030: overviews, Details, and Methodology of Model-Based Analysis*, MNP Report 500113001. MNP Netherlands Environmental Assessment Agency, Bilthoven, The Netherlands.

Bouwman, A. F., Beusen, A. H. W., Billen, G. (2009). Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050. *Global Biogeochemical Cycles*, **23**, GB0A04.

Brink, C., van Grinsven, H., Jacobsen, B. H. *et al.* (2011). Costs and benefits of nitrogen in the environment. In: *The European Nitrogen Assessment*, ed. M. A. Sutton, C. M. Howard, J. W. Erisman *et al.* Cambridge University Press.

Butterbach-Bahl, K., Nemitz, E., Zaehle, S. *et al.* (2011). Nitrogen as a threat to the European greenhouse balance. In: *The European Nitrogen Assessment*, ed. M. A. Sutton, C. M. Howard, J. W. Erisman *et al.* Cambridge University Press.

Carlsson-Kanyama, A. and González, A. D. (2009). Potential contributions of food consumption patterns to climate change. *American Journal of Clinical Nutrition*, **89** (supplement), 1740S–1709S.

Carlsson-Kanyama, A., Dreborg, K. H., Moll H. C. and Padovan, D. (2008). Participative backcasting: a tool for involving stakeholders in local sustainability planning. *Futures*, **40**, 34–46.

Chen, D., Suter, H., Islam, A. *et al.* (2008). Prospects of improving efficiency of fertiliser nitrogen in Australian agriculture: a review of enhanced efficiency fertilisers. *Australian Journal of Soil Research*, **46**, 289–301.

Clarke, L., Edmonds, J., Jacoby, H. *et al.* (2007). Scenarios of greenhouse gas emissions and atmospheric concentrations, Sub-report 2.1A of Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Department of Energy, Office of Biological and Environmental Research, Washington, DC.

Cordell, D., Drangert, J.-O. and White, S. (2009). The story of phosphorous: global food security and food for thought. *Global Environmental Change*, **19**, 292–305.

Corvalan, C., Hales, S. and McMichael, A. (2005). Ecosystems and human well-being: health synthesis, report prepared by WHO as contribution to the Millennium Ecosystem Assessment, WHO, Geneva. www.millenniumassessment.org.

De Vries, W., Wamelink, W., Van Dobben, H. *et al.* (2010a). Use of dynamic soil vegetation models to assess impacts of nitrogen deposition on species composition and to estimate critical loads: an overview. *Ecological Applications* (in press).

De Vries, W., Kros, J., Reinds, G. J. *et al.* (2010b). INTEGRATOR: a modelling tool for European-wide assessments of nitrogen and greenhouse gas fluxes in response to changes in land cover, land management and climate: calculation procedures, application methodology and examples of scenario results. Alterra Wageningen UR, Wageningen, The Netherlands.

De Vries, W., Kros, J., Reinds, G. J. *et al.* (2010c). Assessment of nitrogen and green house gas fluxes at the European scale in response to land cover, livestock and land management change. *Agriculture, Ecosystems and Environment* (in preparation).

De Vries, W., Leip, A., Reinds, G. J. *et al.* (2011). Geographic variation in terrestrial nitrogen budgets across Europe. In: *The European Nitrogen Assessment*, ed. M. A. Sutton, C. M. Howard, J. W. Erisman *et al.* Cambridge University Press.

Dise, N. B., Ashmore, M., Belyazid, S. *et al.* (2011). Nitrogen as a threat to European terrestrial biodiversity. In: *The European Nitrogen Assessment*, ed. M. A. Sutton, C. M. Howard, J. W. Erisman *et al.* Cambridge University Press.

Domene, L. and Ayres, R. U. (2001). Nitrogen's role in industrial systems. *Journal of Industrial Ecology*, **5**, 77–103.

EC4MACS (2010). www.ec4macs.eu

EFMA (2007). Forecast of food, farming and fertilizer use in the European Union 2007–2017. European Fertilizer Manufacturers Association, Brussels.

Engström, R.J., and Carlsson-Kanyama, A. (2004). Food losses in foos service institutions – examples from Sweden. *Food Policy*, **29**, 203–213.

Erisman, J. W., Sutton, M. A., Galloway, J., Klimont, Z. and Winiwarter, W. (2008). 100 years of ammonia synthesis: how a single patent changed the world. *Nature Geosciences*, **1**, 636–639.

Erisman, J. W., van Grinsven, H., Lei, A., Mosier, A. and Bleeker, A. (2010). Nitrogen and biofuels; an overview of the current state of knowledge. *Nutrient Cycling in Agroecosystems*, **86**, 211–223.

EUROSTAT (2009). Statistical tables (population statistics). http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/themes

Eururalis (2010). www.eururalis.eu

FAO (2003). *World agriculture: towards 2015/2030: An FAO Perspective*, ed. J. Bruinma. Earthscan Publications, London.

FAO (2009). FAOSTAT database collections. Food and Agriculture Organization of the United Nations, Rome. (http://faostat.fao.org/)

FEFAC (2008). *Feed and Food Statistical Yearbook 2007*. FEFAC-European Feed Manufacturers Federation, Brussels.

Fischer, G., Prieler, S., van Velthuizen, H. *et al.* (2010a). Biofuel production potentials in Europe: sustainable use of cultivated land and pastures. Part I: Land productivity potentials. *Biomass and Bioenergy*, **34**, 159–172.

Fischer, G., Prieler, S., van Velthuizen, H. *et al.* (2010b). Biofuel production potentials in Europe: sustainable use of cultivated land and pastures. Part II: Land use scenarios. *Biomass and Bioenergy*, **34**, 173–187.

Forkes, J. (2007). Nitrogen balance for the urban food metabolism of Toronto, Canada, *Resources Conservation and Recycling*, **52**, 74–94.

Fujino, J., Nair, R., Kainuma, M., Masui, T. and Matsuoka, Y. (2006). Multi-gas mitigation analysis on stabilization scenarios using AIM global model. Multigas Mitigation and Climate Policy. *Energy Journal*, Special Issue **3**, 343–354.

GAINS (2010). http://gains.iiasa.ac.at

Galloway, J. N., Aber, J. D., Erisman, J. W. *et al.* (2003). The nitrogen cascade. *BioScience*, **53**, 341–356.

Galloway, J., Townsend, A., Erisman, J. W. *et al.* (2008). Transformation of the nitrogen cycle: recent trends, questions, and potential solution. *Science*, **320**, 889–892.

Giller, K. E. (2001). *Nitrogen Fixation in Tropical Cropping Systems*. CAB International, Wallingford,UK.

Giller, K. E. and Merckx, R. (2003). Exploring the boundaries of N_2-fixation in non-legumes: an hypothetical and experimental framework. *Symbiosis*, **35**, 3–17.

Grizzetti, B., Bouraoui, F., Billen, G. *et al.* (2011). Nitrogen as a threat to European water quality. In: *The European Nitrogen Assessment*, ed. M. A. Sutton, C. M. Howard, J. W. Erisman *et al.* Cambridge University Press.

GTAP (2010). www.gtap.agecon.purdue.edu/

Hemmat, A. and Adamchuk, V. I. (2008). Sensor systems for measuring soil compaction: review and analysis. *Computers and Electronics in Agriculture*, **63**, 89–103.

Herring, J. R. and Fantel, R. J. (1993). Phosphate rock demand into the next century: impact on world food supply. *Natural Resources Research*, **2**, 226–246.

Hettelingh, J.-P., Posch, M. and Slootweg, J. (eds.) (2008). Status of the critical load database and impact assessment. In: *Critical Load, Dynamic Modelling and Impact Assessment in Europe*, CCE Status Report 2008. www.rivm.nl/cce

Hettelingh, J.-P., De Vries, B. and Hordijk, L. (2009). Integrated assessment., In: *Principles of Environmental Sciences*, J. Boersema, and L. Reijnders, ed., Springer, New york, pp. 385–417.

Howarth, R., Bringezu, S., Bekunda, M. *et al.* (2009). Rapid assessment on biofuels and the environment: overview and key findings. In: *Biofuels: Environmental Consequences and Interactions with Changing Land Use*, ed. R. W. Howarth and S. Bringezu, Cornell University, Ithaca, NY, pp. 1–13.

International Fertilizer Industry Association: Production and International Trade Committee (IFA-PITCom) (2009). World nitrogen industrial use in 2007. International Fertilizer Industry Association, Shanghai.

Jensen, M. H. (1997). Hydroponics. *Hortscience*, **32**, 1018–1021.

Kantor, L. S., Lipton, K., Manchester, A. and Oliveira, V. (1997). Estimating and addressing America's food losses. *Food Review*, **20**, 2–12.

Ladha, J. K. and Reddy, P. M. (2003). Nitrogen fixation in rice systems: state of knowledge and future prospects. *Plant and Soil*, **262**, 151–167.

Ladha, J. K., Pathal, H., Krupnik, T. J., Six, J. and Van Kessel, C. (2005). Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. *Advances in Agronomy*, **87**, 85–156.

Leip, A., Achermann, B., Billen, G. *et al.* (2011). Integrating nitrogen fluxes at the European scale. In: *The European Nitrogen Assessment*, ed. M. A. Sutton, C. M. Howard, J. W. Erisman *et al.* Cambridge University Press.

Liu, H. B., Xie, D. and Wu, W. (2008). Soil water content forecasting by ANN and SVM hybrid architecture. *Environmental Monitoring and Assessment*, **143**, 187–193.

Llorens Abando, L. and Martinez Palou, A. M. (2006). Main stages in the meat food chain in Europe, Statistics in focus, Agriculture and Fisheries 6/2006. EUROSTAT, Luxembourg.

Londo, M., Lensink, S., Wakker, A. *et al.* (2010). The REFUEL EU road map for biofuels in transport: application of the project's tools to some short-term policy issues. *Biomass and Bioenergy*, **34**, 244–250.

Lysen, E., Van Egmond, S., Dornburg, V. *et al.* (2008). Biomass assessment: global biomass potentials and their links to food, water, biodiversity, energy modelling and economy, Main report. Publisher: Netherland Environmental Assessment Agency (MNP), Bilthoven, The Netherlands.

MA (2005). *Ecosystems and Human Well-Being: Scenarios*, Volume 2, *Findings of the Scenarios Working Group, Millennium Ecosystem Assessment*. S. R. Carpenter, P. L. Pingali, E. M. Bennett and M. B. Zurek, ed., Island. Press, Washington DC.

Magid, J., Eilersen, A. M., Wrisberg, S. and Henze, M. (2006). Possibilities and barriers for recirculation of nutrients and organic matter from urban to rural areas: a technical theoretical framework applied to the medium-sized town Hillerød, Denmark. *Ecological Engineering*, **28**, 44–54.

Minchin, F. R., Summerfield, R. J., Hadley, P., Roberts, E. H. and Rawsthorne, S. (1981). Carbon and nitrogen nutrition of nodulated roots of grain legumes. *Plant, Cell and Environment*, **4**, 5–26.

Moldanová, J., Grennfelt, P., Jonsson, Å. *et al.* (2011). Nitrogen as a threat to European air quality. In: *The European Nitrogen Assessment,* ed. M. A. Sutton, C. M. Howard, J. W. Erisman *et al.* Cambridge University Press.

Murase, H. (2000). Artificial intelligence in agriculture. *Computers and Electronics in Agriculture*, **29**, 1–2.

NEU (2010). www.nitroeurope.eu.

Nowicki, P. L., van Meijl, J. C. M., Kneirim, A. *et al.* (2006). Scenar 2020: scenario study on agriculture and the rural world EC. Directorate Gen. for Agriculture and Rural Development, Brussels.

Nakicenovic, N., Alcamo, J., Daris, G., *et al.* (2006). Special *Report on Emissions Scenarios. Working group III of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK, 2000.

OECD (2008). Environmental performance of agriculture in OECD countries since 1990. Organisation for Economic Co-operation and Development, Paris.

Oenema, O., Bleeker, A., Braathen, N. A. *et al.* (2011). Nitrogen in current European policies. In: *The European Nitrogen Assessment*, ed. M. A. Sutton, C. M. Howard, J. W. Erisman *et al.* Cambridge University Press.

Olfs, H. W., Blankenau, K., Brentrup, F., *et al*. (2005). Soil- and plant-based nitrogen-fertilizer recommendations in arable farming. *Journal of Plant Nutrition and Soil Science*, **168**, 414.

Pagola, M., Ortiz, R., Irigoyen, I. *et al.* (2009). New method to assess barley nitrogen nutrition status based on image colour analysis: comparison with SPAD-502. *Computers and Electronics in Agriculture*, **65**, 213–218.

Pate, J. S. and Layzell, D. B. (1981). Energetics and biological costs of nitrogen assimilation. In: *The Biochemistry of Plants*, ed. Miflim, B. J. and Lea, P. J. Academic Press, San Diego, CA, pp. 1–41.

Phene, C. J. (1989). Techniques for computerized irrigation management. *Computers and Electronics in Agriculture*, **3**, 189–208.

Posch M., Hettelingh, J.-P., Slootweg, J. and Maas, R. (2008). Illustrative dynamic modeling applications for use in support of European air pollution abatement policies. In: *Critical Load, Dynamic Modelling and Impact Assessment in Europe*, J.-P., Hettelingh, M. Posch, and J., Slootweg, eds. CCE Status Report 2008. www.pbl.nl/cce

Prud ' homme, M. (2009). *Global Fertilizers and Raw Materials Supply and Supply/Demand Balances*. International Fertilizer Industry Association, Shanghai.

Resy, D.S., Hasand, C.M., Bleeker, A. *et al*. (2004). Societal Choice and Communicating in the European Nitrogen Challenge. In: *The European Nitrogen Assessment*, ed. M.A. Sutton, C.M. Hasand, J.W. Erisman *et al*., Cambridge University Press.

Representative Concentration Pathways (2010). www.iiasa.ac.at/web-apps/tnt/RcpDb

Riahi, K., Gruebler, A. and Nakicenovic, N. (2007). Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technological Forecasting and Social Change*, **74**, 887–935.

Rienks, W. (ed.) (2008). *The Future of Rural Europe*. Wageningen University Research and Netherlands Environmental Assessment Agency, Wageningen, The Netherlands.

Seitzinger, S. P., Mayorga, E., Bouwman, A. F. *et al.* (2010). Global river nutrient export: a scenario analysis of past and future trends. *Global Biogeochemical. Cycles*, **24**, GB0A08.

Slaughter, D. C., Giles, D. K. and Downey, D. (2008). Autonomous robotic weed control systems: a review. *Computers and Electronics in Agriculture*, **61**, 63–78.

Smil, V. (2002). Eating meat: evolution, patterns, and consequences. *Population and Development Review*, **28**, 599–639.

Stehfest, E., Bouwman, A. F., van Vuuren, D. P. *et al.* (2009). Climate benefits of changing diet. *Climatic Change*, **95**, 83–102.

Sutton, M. A., Nemitz, E., Erisman, J. W. *et al.* (2007). Challenges in quantifying biosphere–atmosphere exchange of nitrogen species. *Environmental Pollution*, **150**, 125–139.

Svirejeva-Hopkins, A. and Schellnhuber, H.-J. (2008). Urban expansion and its contribution to the regional carbon emissions: using the model based on the population density distribution. *Ecological Modelling*, **216**, 208–216.

Svirejeva-Hopkins, A., Reis, S., Magid, J. *et al.* (2011). Nitrogen flows and fate in urban landscapes. In: *The European Nitrogen Assessment*, ed. M. A. Sutton, C. M. Howard, J. W. Erisman *et al.* Cambridge University Press.

Tanigaki, K., Fujiura, T., Akase, A. and Imagawa, J. (2008). Cherry-harvesting robot. *Computers and Electronics in Agriculture*, **63**, 65–72.

Tilman, D., Hill, J. and Lehman, C. (2006). Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science*, **314**, 1598–1600.

UN (2004). World population to 2300. United Nations Publications, New York.

Van Drecht, G., Bouwman, A. F., Harrison, J. and Knoop, J. M. (2009). Global nitrogen and phosphate in urban wastewater for the period 1970 to 2050. *Global Biogeochemical. Cycles*, **23**, GB0A03.

Van Egmond, Bresser, T. and Bouwman, L. (2002). The European Nitrogen case. *Ambio* **31**, 72–78.

Van Henten, E. J., Van ' t Slot, D. A., Hol, C. W. J. and Van Willigenburg, L. G. (2009). Optimal manipulator design for a cucumber harvesting robot. *Computers and Electronics in Agriculture*, **65**, 247–257.

van Vuuren, D., den Elzen, M., Lucas, P. *et al.* (2007). Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Climatic Change*, **81**, 119–159.

Verburg, P. H., Veldkamp, A. and Rounsevell, M. D. A. (2006). Scenario-based studies of future land use in Europe. *Agriculture, Ecosystems and Environment*, **114**, 1–6.

Willett, W. C. (2001). *Eat, Drink, and Be Healthy: The Harvard Medical School Guide to Healthy Eating*. Simon & Schuster, New York.

Yu, L., Li, D., Yu, S. *et al.* (2006). Research advances in slow/controlled release fertilizers. *Shengtaixue Zazhi*, **25**, 1559–1563.