Available online at www.sciencedirect.com
SCIENCE DIRECT®
Agriculture, Ecosystems and Environment 116 (2006) 4–14
Agriculture Ecosystems & Environment
www.elsevier.com/locate/agee

The role of nitrogen in world food production and environmental sustainability

B. Eickhout*, A.F. Bouwman, H. van Zeijts

Netherlands Environmental Assessment Agency, National Institute for Public Health and the Environment, P.O. Box 1, 3720 BA Bilthoven, The Netherlands

Available online 18 April 2006

Abstract

On the basis of the FAO projection 'World Agriculture: Towards 2015/2030' we direct our discussion to food production, the consequences for land use, efficiency of nitrogen (N) and losses of reactive N to the environment during 1995–2030. According the FAO, global food production can keep pace with the increase in food demand in the coming three decades. However, according the projection used here, there will be a major global increase (8%) in arable land, most of it in developing countries and with a major impact on the extent of tropical forests. Further forest clearing may occur to compensate for declining soil productivity due to land degradation. Despite improvements in the N use efficiency, total reactive N loss will grow strongly in the world's increasingly intensive agricultural systems. In the 1995–2030 period emissions of reactive N from intensive agricultural systems will continue to rise, particularly in developing countries. Therefore, the increase of N use efficiency and further improvement of agronomic management must remain high on the priority list of policy makers.

Keywords: Agriculture; Food security; Land use; Crop production; Environment; Reactive nitrogen; Sustainable development

1. Introduction

For many decades, food security and hunger have been among the most important issues playing a role in the global political arena. At the first World Food Summit in 1974, political leaders from around the world set a goal to eradicate hunger in the world within 10 years. This ambitious goal was not met, leading to new goals at the second World Food Summit in 1996. The world leaders committed themselves to reduce the number of chronically undernourished by half by the year 2015. This target has been endorsed at many other meetings since then and is now known as one of the eight millennium development goals (MDGs) of the United Nations (United Nations, 2001). The MDGs commit the international community to adopt an extended view on development and recognize the importance of creating a global partnership to achieve sustainable economic growth.

The term 'sustainable economic growth' embraces the marriage of economy and ecology and has been introduced by Brundtland (1987) as sustainable development. The Brundtland report emphasizes the importance of development as a prerequisite for peace, security and protection of the environment. Hence, hunger eradication needs to be addressed within ecological constraints.

The seventh MDG (ensuring environmental sustainability) is poorly elaborated in terms of measurable indicators. The United Nations General Assembly concluded that the selection of indicators for the environmental MDG would need further refinement (United Nations, 2001). So far, however, only greenhouse gas emissions, the extent of forest area and the access to improved water sources and sanitation have been defined as indicators. These are insufficient when it comes to assessing the potential for food security within environmental constraints (MNP, 2005).

This paper focuses on the relationships between food production, the area of agricultural land and emissions of reactive nitrogen (N). Nitrogen is an essential element for plant growth and a key element of agricultural input. Rapid

* Corresponding author. Tel.: +31 30 274 2924; fax: +31 30 274 4464.
E-mail address: Bas.Eickhout@mnp.nl (B. Eickhout).

0167-8809/$ – see front matter
doi:10.1016/j.agee.2006.03.009

increases of crop yields became possible when synthetic N fertilizer became available after the discovery of the Haber–Bosch process in the early 20th century (Smil, 2001). However, increased use of N fertilizers has also led to increased N losses from agro ecosystems, especially since the 1950s. Distribution of fertilizer N across the globe is very uneven. In some areas N is used excessively and leads to N pollution, causing a host of problems for human and ecological health. Other parts of the world suffer from reduced soil fertility, diminished crop production, and other consequences of inadequate N supply (Mosier et al., 2004).

The recovery of fertilizer N in global crop production is about 50% (Krupnik et al., 2004; Smil, 1999). The surplus may accumulate in soils, or be lost to air, groundwater and surface water via various pathways. Losses from the soil-plant system are due to denitrification in the form of gaseous dinitrogen (N_2), nitrous oxide (N_2O) and nitric oxide (NO), volatilization of ammonia (NH_3), leaching of nitrate (NO_3^-), runoff and erosion (Bouwman et al., 2002a; FAO/IFA, 2002). The environmental consequences of the different compounds are diverse. Essentially, all emitted NH_3 is returned to the surface by deposition, one of the causes of soil acidification since the early 1980s (Van Breemen et al., 1982). Moreover, there is growing concern about the eutrophication of natural ecosystems and loss of biodiversity due to N deposition (Bouwman et al., 2002c). Nitrous oxide is one of the so-called greenhouse gases, contributing 6% of the anthropogenic greenhouse effect; it also contributes to the depletion of stratospheric ozone (IPCC, 2001). Finally, NO_3^- is an important pollutant of groundwater and surface water (Heathwaite, 1993; Johnes and Burt, 1993). Increasing N inputs to freshwater systems can, if sufficient P is present, cause eutrophication, generally accompanied by decreased diversity of both plant and animal species (Schindler, 1977; Vollenweider, 1992).

The aim of this paper is to provide insight into the impact of historical and future changes of food production on the environmental losses of reactive N from agriculture. After introducing the data and methods (Section 2), we will discuss the changes in food consumption (Section 3) and production (Section 4), land use (Section 5), nitrogen use efficiencies (Section 6), and losses of reactive N (Section 7) in different regions of the world for the period 1970–2030.

2. Data and methods used

For our analysis we used historic data for food demand and production from FAOSTAT (for the period 1970–1995; FAO, 2001) and a projection to 2030 from the FAO study 'World Agriculture: Towards 2015/2030' (Bruinsma, 2003). This projection has been transformed into spatial land use distributions with the Integrated Model to Assess the Global Environment (IMAGE-team, 2001). The IMAGE model generates 0.5 by 0.5 degree global land cover maps providing the grid cells covered by either agriculture (crops and grassland) or natural ecosystems. Four broad groups of crops were distinguished: grassland, wetland rice, leguminous crops (pulses, soybeans) and upland crops. Within the category of grassland, we distinguished between grassland in intensive (landless and mixed) and pastoral livestock production systems and (semi)-natural and marginal grassland according to Bouwman et al. (2005a), who used estimates from Seré and Steinfeld (1996). Here, we use the term intensive agricultural systems for all mixed and industrial (landless) livestock production systems and all arable agriculture.

The methodology for N balances calculation was taken primarily from Bouwman et al. (2005b). Many countries have vast areas of extensively used pastoral (semi)-natural and marginal grassland, typically with small N inputs. In contrast, other countries have primarily mixed and landless systems characterized by much larger N inputs. To make a good comparison between different countries, we excluded the areas of pastoral (semi)-natural and marginal grassland, and consider the N balances for crop and mixed and landless livestock production systems together. Including pastoral, natural and marginal grassland would give an unrealistic impression of the intensity of agricultural systems.

N inputs in the surface N balance include biological N fixation, atmospheric N deposition, application of synthetic N fertilizer, and animal manure and animal N excreted during grazing. Outputs include N removal by crop harvesting and grazing. The N balance calculation is a static approach, i.e., soil N changes were neglected. The N balance surplus consists of NH_3 volatilization, denitrification, leaching and surface runoff. All surface N balance input and output terms were allocated to the 0.5 by 0.5 degree resolution according to the fractions of the grid cells covered by wetland rice, leguminous crops, upland crops and fertilized grassland.

Mean N application rates via chemical fertilizer for the mid-1990s were taken directly from IFA/IFDC/FAO (2003), with a few exceptions. For 1970 the application rates were multiplied with the change in crop yield compared to 1995 (Bruinsma, 2003) thus ignoring changes in crop N recovery.

For N excretion rates per animal, data from Van der Hoek (1998) were used. All manure produced by pigs and poultry was assumed to be collected. For ruminants, the fraction of the manure that is excreted in pastures was calculated from the fraction grass in the ration according to Bouwman et al. (2005a) and the complement was assumed to be stored in animal houses. The animal manure produced within intensive and pastoral systems is distributed over different animal waste management systems according to Bouwman et al. (2005b). Animal manure available for application to cropland and grassland equals all collected manure corrected for manure used as fuel and building purposes. Within the intensive and pastoral systems in most developed countries, we assumed that 50% of the collected animal manure was applied to arable land and 50% to grassland. In most developing countries 95% of the collected manure is