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Analysis

Estimating stocks and flows of nitrogen: Application of dynamic nutrient balance to European agriculture

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ABSTRACT

This study elaborates the dynamic nutrient balance model and applies it to analyze nitrogen use and nitrogen efficiency in agriculture. We use publicly available agricultural production data to estimate the net inflows, stocks and outflows of nitrogen for 14 European countries in years 1961–2009. The dynamic model allows us to analyze the trends in the nitrogen stocks and flows over time, and break down the total outflow of nitrogen into flows to water, air and soil. We argue that the nitrogen outflow, modeled as the decay of nitrogen stock, provides a more reliable and robust agri-environmental indicator than the conventional nutrient balance. Mathematically, the nutrient balance is an interval scale measure, whereas the nitrogen stock and the outflow from stock are ratio scale measures. Nitrogen efficiencies, calculated based on the nitrogen stocks, provide useful and insightful information beyond the conventional eco-efficiency measures defined from the nitrogen balances. The results of this paper can be used as input data for more comprehensive eco-efficiency or productivity analysis and for the evaluation and design of agri-environmental policies in Europe.

1. Introduction

Sustainable nutrient management in agriculture is one of the major environmental issues in Europe. Nutrients, such as nitrogen and phosphorus, are essential elements required for soil fertility and plant growth. On the one hand, nutrient deficiency can cause soil degradation resulting in declining fertility in areas under crop or forage. On the other hand, excessive use of nutrient beyond immediate needs of crop and forage can pose a threat to the environment, in particular to water systems. For example, agricultural run-offs carrying nutrients into water bodies can stimulate growth of algae and water weeds. This process can lead to eutrophication of surface waters, which is a major environmental concern in many countries. The balance between nutrients applied to agricultural soil and removed from the soil with harvested crops is essential not only for abating environmental pollution caused by agricultural activities, but also for ensuring sustainable use of soil resources.

A number of existing agri-environmental policies in the EU intend to limit the environmental damages from excessive use of nutrients. For instance, in the Community Directive on Nitrates (EEC, 1991) the aim is to reduce water pollution caused or induced by nutrients from agricultural sources. In the EU Water Framework Directive (EU WFD, 2000), EU member states are obliged to achieve good qualitative and quantitative status of all water bodies by 2015. In the Rural Development Program (EC, 2005), the issue of excess nutrients is addressed by a number of measures taken through reduction of fertilizer use. In total, a set of 28 agri-environmental indicators, proposed in the European Commission Communication (COM, 2006), aims to assess the interactions between agriculture and the environment.

Nutrient balance (OECD, 1997, 2001, 2007a, 2007b; see also Parris, 1998) (henceforth NB) is extensively used in agricultural and environmental studies (e.g., Van Eerdt and Fong, 1998; Slak et al., 1998; Salo and Turtola, 2006; Gaj and Bellaloui, 2012; Sassenrath et al., 2012). The NB aims to measure the potential damage to the environment through the nutrient excess. Three main varieties exist to the NB approach: farm gate, soil surface, and soil system (see for a review e.g., Oenema et al., 2003; Hoang and Alauddin, 2010). While the main difference among these approaches rests on the definition of the boundary of the defined system and nutrient inputs and outputs, the methods are inspired by the fundamental law of mass conservation and are based on the conventional material balance equation (see e.g., the seminal article by Ayres and Kneese, 1969).

The recent study by Kuosmanen and Kuosmanen (2013) critically examined the conventional approach to material balance accounting as applied to nutrients in agriculture arguing that the NB approach ignores the accumulation of nutrients to the environment and importantly, overlooks the dynamic nature of the nutrient cycles. By applying the standard model of capital accumulation in production economics, Kuosmanen and Kuosmanen propose a dynamic model of nutrient balance (henceforth DNB). Based on the intuitive link between the capital stock and investment, used in production economics, and the stock and flow of a nutrient, the DNB allows to model

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nutrient stocks in agriculture. The insights of the dynamic modeling were demonstrated by an empirical application to Finnish agriculture by estimating nutrient flows and stocks of nitrogen and phosphorus for a 48-year period.

The objectives of this paper are three fold:

1) elaborate the advantages of the DNB over the static NB approach;
2) estimate stocks and flows of nitrogen for 14 European countries in years 1961–2009;
3) analyze and compare nitrogen efficiency of those countries.

Regarding the first objective, we underline that the DNB does not only concern stock versus flow comparison, but more importantly, about outflow versus net inflow of a nutrient. In this paper, the net inflow of a nutrient is represented by estimates of the NB approach, while the outflow is modeled as the decay of the nutrient stock. We argue that the outflow is both conceptually and mathematically a better indicator of environmental pressure than the conventional NB.

Our second objective is to estimate nitrogen net inflows, stocks and outflows for 14 European countries in 1961–2009 based on publicly available data of agricultural production. The country specific estimates are available as Online Supplement to this article: we believe that these estimates may provide useful input data for other researchers, who are interested in using nitrogen stock estimates in their own research. The empirical application demonstrates that the DNB is applicable to a large number of countries.

Currently, the static NB measure is widely used as an agri-environmental indicator to support policy making of the EU and its member countries. For instance, NB is included in the list of the agri-environmental indicators of COM (2006), and it is also adopted in EEC (1991), EU WFD (2000), and EC (2005), among other agri-environmental policies. Unfortunately, the static NB indicator is highly sensitive to temporary fluctuations due to weather conditions, measurement errors, omitted variables and other sources of noise. In the short term assessment, the static NB indicator can significantly under- or overestimate the environmental pressure due to nutrient emissions from agriculture. Our empirical results demonstrate that the nitrogen outflow, calculated based on the DNB model, provides a more reliable and robust agri-environmental indicator.

As a first step towards policy analysis, our third objective is to make cross-country comparisons of nitrogen efficiency, defined as a ratio of economic value of agricultural production to nitrogen stock. Similar to partial productivity measures, nitrogen efficiency allows one to compare countries in terms of economic output produced per unit of environmental bad.[1] By combining economic and environmental performances of countries in one measure, one can rank countries according to how much economic output is created per unit of nitrogen stock. Since the estimates of the decay rate and the initial stock levels are somewhat rough, we present a sensitivity analysis to explore robustness of the DNB with respect to these parameters.

The rest of the paper is structured as follows. Section 2 briefly recaptures the theoretical framework of the DNB model. Section 3 sets the background for the empirical research. The results of the DNB in cross-country comparisons are demonstrated in Sections 4 and 5. Following Section 6 presents some sensitivity analyses to assess the robustness of the DNB estimator. Section 7 concludes.

[1] The nitrogen efficiency considered in this study can be extended towards more comprehensive total factor productivity and eco-efficiency measures that consider multiple good and bad outputs and material and immaterial inputs. For further discussion and references, see, e.g., Färe et al. (1989), Kuosmanen and Kortelainen (2005), and Hoang and Alauddin (2012).

2. Dynamic Nutrient Balance

2.1. Theoretical Framework

In this section we introduce net inflow, stock and outflow of a nutrient more formally. Consider a number of countries $i = 1, \dots, n$ that apply a nutrient z (e.g., nitrogen or phosphorus) in their agricultural activities. The quantity of nutrient z in a time period t is defined by its annual input and output flows, $\mathbf{x}_{it}$ and $\mathbf{y}_{it}$. While vector $\mathbf{x}_{it}$ represents the quantities of nutrient inputs, such as chemical fertilizers and livestock manure, vector $\mathbf{y}_{it}$ includes the quantities of nutrient absorbed by outputs, such as crops and forage.

Further, the conventional NB (see e.g., OECD, 2007a, 2007b) is calculated as the difference between the total nutrients in the inputs and the total nutrients in the outputs. When resulted value of the NB is positive it is called a surplus, when the NB value is negative it is called a deficit. Hence, the estimate of the NB of nutrient z in period t for country i can be written in the following form:

$$h_{it} = \mathbf{a}_i'\mathbf{x}_{it} - \mathbf{b}_i'\mathbf{y}_{it}, \tag{1}$$

where coefficients $\mathbf{a}_i$ and $\mathbf{b}_i$ are non-negative vectors of nutrient content in the inputs and outputs, and $\mathbf{x}_t$ and $\mathbf{y}_t$ are vectors specific to country i.

In general, nutrient content in inputs and outputs varies from country to country and from one region to another within a country. It depends on a number of factors, such as the type of livestock, the grazing systems, the nutrient content of the different fodder and feedstuffs used for livestock, the type of harvested crop, among other factors. In this study, to convert the data into nutrient contents, we use country specific coefficients available at the Eurostat/OECD gross nutrient balance data collection, which were originally provided by national statistical offices under the framework of the Joint Eurostat/OECD Questionnaire.

Estimates of the NB (Eq. (1)) are generally used in cross-country comparisons of nutrient use (OECD, 2008) in attempt to reveal the most vulnerable national areas under water, air and soil pollution. While some studies (e.g., Lord et al., 2002; Schweigert and Van der Ploeg, 2002) focus on the analysis of the NB estimates and their spatial distributions at the national level, other studies look at the development of the NB at the regional or even farm level (e.g., Maticic, 1999; Salo et al., 2007). Studies that apply the NB approach treat nutrients as flow pollutants, which assume an immediate effect on the environment. However, nitrogen and phosphorus are primary examples of stock pollutants: they accumulate to the soil and have delayed impacts occurring over time.[2] For the sake of generality, we further refer to the NB estimates h_{it} as net inflow of nutrient.

Estimated nutrient net inflow (Eq. (1)) in a region or a country can be useful in static cross-country comparisons that consider a single year or a few years only. However, if one is interested in analyzing the development of nutrient accumulation in a country or a region, or assesses nutrient accumulation in cross-country comparisons over time, it is important to consider the dynamic nature of the nutrient cycle. To calculate the stock of nutrient z in country i, we apply the model of DNB developed in Kuosmanen and Kuosmanen (2013). Following their reasoning, the quantity of nutrient stock Z in year t can be estimated by an accumulation of past nutrient net inflows h_{it} depreciated over time as:

$$Z_{it} = (1 - \delta_i) Z_{i,t-1} + h_{it}. \tag{2}$$

In Eq. (2), Z_{it} and $Z_{i,t-1}$ represent the levels of nutrient stocks in periods t and $t - 1$ in country i, respectively, $\delta_i \in [0, 1]$ is the decay rate.

[2] Accumulation of nutrient into a stock is commonly accepted and used in other fields, such as biology, ecology, atmospheric science, among others (e.g., Dolan et al., 1981; Koerselman and Meuleman, 1996; Ertsen et al., 1998; Iho and Laukkanen, 2012).