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Methodological and Ideological Options

Modeling Cumulative Effects of Nutrient Surpluses in Agriculture: A Dynamic Approach to Material Balance Accounting

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ABSTRACT

Nutrients such as nitrogen and phosphorus have a dual role as inputs to crop production and as pollutants to water, air, and soil. The nutrient surplus measures are frequently used as indicators of environmental performance or eco-efficiency at micro level of individual farms and at macro levels of regions and countries. However, the static material balance accounting ignores an important dimension of the nutrient cycle: the time. Nutrients accumulate in soil, causing delayed effects and persistent harm to the environment. In this paper we propose a dynamic model of material balance, following the standard model of capital accumulation used in production economics. Using data of agricultural production in Finland in the years 1961–2009, we show that it is possible to estimate the stocks of nitrogen and phosphorus accumulated in the soil using information and data that are readily available. The dynamic model allows us to estimate not only the stocks of nutrients, but also the outflow of nutrients to water and air. Better understanding of flows and stocks of nutrients can provide insights to support managerial and policy decisions.

1. Introduction

Nutrient emissions from agricultural activities such as planting, fertilizing, harvesting, confined animal facilities and grazing affect the environment in many ways. Water and air pollution from agriculture causes severe environmental problems. For instance, leaching of nutrients, such as nitrogen and phosphorus from excessively fertilized arable areas into water bodies stimulate growth of aquatic plant life, such as algae and water weeds. Eutrophication of surface waters damages the biodiversity of rivers and lakes, and impairs their use for drinking water, fishing and recreational purposes. Further, excessive applications of inorganic fertilizers to agricultural soil and volatilized ammonia contained in livestock manure contribute to air emissions. However, nitrogen and phosphorus are also essential inputs of plant growth. The balance between nutrients added to the soil and removed from the soil is critical for the sustainable agriculture and efficient resource use. While excessive nitrogen and phosphorus use damages the environment, nutrients deficiency can cause a decline in soil fertility and crop yields.

To estimate the environmental pressures from nutrients use in agriculture at the aggregate level of countries, the OECD and Eurostat apply and develop the nutrient balance approach (OECD, 2001, 2007a, 2007b, 2008). Drawing on the notion of nutrient cycle, in this approach the nutrient surplus is calculated as the difference between the total quantity of nutrient inputs entering an agricultural system (mainly from chemical fertilizers and livestock manure) and the quantity of nutrient outputs leaving the system (mainly due to uptake of nutrients in crop and forage).

The material balance approach is widely claimed to be based on the fundamental law of mass conservation (e.g., Ayres and Kneese, 1969; Georgescu-Roegen, 1986; Daly, 1997; Baumgärtner, 2004; Pethig, 2006; Ebert and Welsch, 2007; Førsund, 2009; among others). However, the conventional material balance equation completely ignores time. Strictly speaking, it is only applicable to the flow pollutants which affect the environment immediately (e.g., the burning of fossil fuels to generate electricity has an immediate effect on air quality). Nutrients such as nitrogen and phosphorus are prime examples of stock pollutants,[1] which accumulate in the soil over time and have delayed effects that occur over time. Therefore, to analyze the impact of an excessive use of nutrients, we find it important to take the time horizon, and the nature of nutrients as stock of pollutants, explicitly into account.

The nutrient balance methods are also widely used for developing indicators of environmental performance in agriculture, both at the farm level and at the aggregated levels of regions and countries (e.g., Hoang and Alauddin, 2010; Hoang and Coelli, 2011; Meensela et al., 2010; OECD, 2011; Reinhard and Thijssen, 2000; Reinhard et al., 1999, 2000; Salo and Turtola, 2006; Sheldrick et al., 2002; Shindo et al., 2006; Spiess, 2011). Unfortunately, the nutrient balance ignores the delayed environmental effects that occur over a relatively long time horizon. Moreover, there is also an important practical problem

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[1] We do not draw a distinction between stock and fund pollutants in this study.

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in the use of the nutrient balance as an environmental indicator: it takes negative values for some countries in some periods (see, e.g., OECD, 2011; Section 1.4). Indeed, nutrient deficit often occurs at the farm level. Technically, as the nutrient surplus is defined as the difference between the inputs and outputs of nutrients, it is defined on the interval scale. Although the nutrient surplus figures can be converted to positive values by adding a large enough positive constant to all observations, in general, mathematical operations such as multiplication or division are no longer meaningful. To our knowledge, this problem has not been duly recognized in the previous literature that uses nutrient surplus as an indicator to assess environmental performance in agriculture.

The present paper proposes to address both the theoretical and practical problems noted above by resorting to a dynamic model of material balance. Our model of pollution stock builds upon the standard model of capital accumulation used in production economics. We make an intuitive link between the capital stock and investment, used in production economics, and the stock and flow of a nutrient pollutant. In this interpretation, the conventional nutrient balance estimates based on the material balance represent the flow of a nutrient. We argue that the pollution stock is often more interesting and relevant information. For example, in productivity studies that take into account the environmental effects of production, it may be appropriate and useful to model the pollution stock analogous to the capital stock. Both the nutrient stock and the decay of the nutrient stock (a flow from the stock) are non-negative variables by construction.

To show that the nutrient stocks can be estimated from data that is readily available, and to illustrate the insights that dynamic modeling can provide beyond the static models of material balance, we estimate the nutrient flows and stocks for the Finnish agricultural sector. The two most important nutrients, nitrogen and phosphorus, are examined at the country level for the years 1961–2009. Our results show that annual variation in the nutrient flows is considerably larger than in the nutrient stock or the change of stock. Further, the explicit modeling of nutrient flows allows one to estimate more precisely the pathways of nutrients to water, air, and soil.

We recognize that estimating nutrient flows and stocks at the aggregate level of countries will inevitably ignore heterogeneity of soil, rainfall patterns, temperature, elevation of fields, and other factors that are found to be critically important for the nutrient cycle in micro-level agronomic studies (e.g., Stevenson, 1982; Brady and Weil, 1999; Stevenson and Cole, 1999; Zhou et al., 2006; Sims and Sharpley, 2005; among many others). Further, the model parameters such as the nutrient contents in different inputs and outputs and the decay rates are rather rough estimates based on the scant empirical evidence at the macro level. Of course, the static models of nutrient balance are subject to the similar imprecision; the only additional source of parameter uncertainty in this study concerns the decay rate. Despite the omitted factors and parameter uncertainty, we do believe the macro-level assessment of the nutrient flows and stocks provides useful information and insights. The macroeconomic models that are used for understanding the unemployment, inflation, investment, or international trade are similarly simplified characterizations of the economy, which ignore various issues that are considered important at the micro level of individual firms and consumers. Using this analogy from economics, the approach of this paper could be described as *macro-agronomy*, in contrast to the detailed micro-level orientation of the mainstream agronomy.

Whereas scientists and engineers are trained to pay careful attention to the units of measurement, which immediately leads one to consider the stocks and flows, economists often ignore the units of measurement, assuming that virtually any values can be converted to the money metric. One of the objectives of this paper is to persuade economists to pay more attention to the stocks and flows, and the units of measurement. We must acknowledge that dynamic modeling of material balance is not a novel idea as such. In chemical and industrial engineering, for example, system dynamics models are commonly used for modeling flows and stocks of substances such as oil or gas (e.g., Ford, 1999). The system dynamics models are usually stated in continuous time, but also discrete time models are known in the literature. In the field of life cycle analysis, the recent work by Helmes et al. (2012) develops a model that includes both temporal and spatial aspects in a macro level investigation of eutrophication effects. However, the standard approach to modeling nutrients in agricultural economics relies on the static model. This paper demonstrates that dynamic modeling of nutrient flows and stocks is possible using information and data that are readily available, and shows that dynamic modeling provides useful information and insights beyond the conventional static approaches.

The rest of the paper is organized as follows. Section 2 briefly discusses the distinction between flow and stock pollutants and describe the nitrogen and phosphorus cycles. Section 3 develops the dynamic model of material balance accounting. Section 4 estimates the flows and stocks for nitrogen and phosphorus in Finland. Section 5 concludes.

2. Stock versus Flow Pollutants

A pollutant generally refers to a substance or energy that has undesired effects in the environment. The distinction between the flow and stock pollutants is well recognized in environmental economics (e.g., Perman et al., 2011). The flow pollutants such as noise have the instantaneous effect, and they are absorbed immediately without accumulating in the environment. In contrast, the stock pollutants accumulate in the environment over time, and cause persistent damage. To model flow pollutants, the time element is of no particular interest, and hence static models are appropriate. In contrast, time is essential in the case of stock pollutant, and thus dynamic modeling is needed.

In production economics, inputs of production can be similarly classified as flow or stock variables. Such inputs as materials, energy, and unskilled labor are usually modeled as flow variables. In contrast, different types of capital inputs such as buildings, machinery, ICT equipment and software are typically modeled as stock variables. Human capital that takes the education and experience explicitly into account can also be modeled as a stock variable. The relevant input variable can be the stock of capital or the flow of services provided by the capital stock. However, it is generally recognized in production economics that the total investment in a given year is a poor proxy for the capital input, unless the firm has no past investments, or all the past investments have become completely obsolete.

Nutrients such as nitrogen and phosphorus have a dual role as both productive inputs and pollutants. Within the boundaries of the agricultural production system, the nutrients are desirable inputs that accumulate to the soil in a similar manner as the farm machinery accumulates in the capital stock. When the nutrients exit the boundary of the production system, the nutrients become undesirable outputs that accumulate in the soil, water and air as stock pollutants. In this study, we apply a pragmatic definition and consider the part of the nitrogen stock in the top soil that is available to plants as productive input. The unavailable part is considered as pollution. We admit that this definition of the system boundary is somewhat arbitrary, but from the conceptual point of view, we find it helpful for understanding and modeling the dual role of nutrients.

To be more specific, three nutrient balance approaches have been distinguished in the literature: 1) the farm-gate, 2) the soil surface, and 3) the soil system approaches (e.g., Hoang and Alauddin, 2010; OECD, 2001, 2007a, 2007b; Oenema et al., 2003). The *farm-gate balance* (sometimes referred to as the “black box” approach) considers the amounts of nutrients in all kind of products entering and leaving the farm, ignoring nutrients recycled within the farm. In contrast, the *soil surface approach* accounts for all nutrients that enter the soil via the surface and that leave the soil via crop uptake, allowing for possible changes