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.

Keywords: *conservation of mass; nitrogen balance; phosphorus balance; productivity; stock pollutants.*

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). 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., OECD, 2001, 2007a, 2007b; Oenema *et al.*, 2003; Hoang and Alauddin, 2010). 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 in the storage of nutrients in the soil. This approach is used by the OECD as an environmental indicator to track nitrogen and phosphorus balances. Finally, the *soil system method* records all nutrient inputs and outputs, including nutrient gains and nutrient losses within and from the soil. This approach allows one to separate between the various pathways of nutrient loss and gain within the soil system. In summary, the three approaches differ in how the boundary of the system is defined, and hence the inputs and outputs are also different.

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; Baumgärter 2004; Pethig, 2006; Ebert and Welsch, 2007; and Førsund, 2009; among others). In the context of agriculture, the nutrient balance method is used in a number of recent studies (e.g., Reinhard *et al*., 1999, 2000; Reinhard and Thijssen, 2000; Coelli *et al*., 2007; Lauwers, 2009; Meensela *et al*., 2010; Hoang and Coelli, 2011). 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.

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

In this paper we address this issue by proposing 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.

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.*, 2004, 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.

We must also 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. However, the standard approach to modeling nutrients in agricultural economics relies on the static model. We are not aware of prior studies of applying dynamic material balance modeling to nutrients in agriculture at aggregate level. The main novelty of this paper is to demonstrate that dynamic modeling of nutrient flows and stocks is possible using information and data that are readily available, and to show that dynamic modeling provides useful information and insights beyond the conventional static approaches.

The nutrient balance methods are also increasingly used at the farm or regional levels as indicators of the environmental performance (e.g., Reinhard *et al*., 1999, 2000; Reinhard and Thijssen, 2000; Sheldrick *et al*., 2002; Salo and Turtola, 2006; Shindo *et al*., 2006; Hoang and Alauddin, 2010; Hoang and Coelli, 2011; Spiess, 2011). To make decisions on nutrient management and environmental policy, it is important to ensure that the delayed environmental effects that occur over a relatively long time horizon are taken into account. We believe the dynamic model of nutrient balance proposed in this paper is generally applicable not only at the country level, but also at regional and farm levels. Of course, calibrating the model parameters to take the farm-specific conditions adequately into account can be a challenge, but this is no excuse to ignore the dynamics of the nutrient cycle. Finally, we hope that the proposed dynamic approach might prove useful for modeling the material balance for other stock pollutants (e.g., toxic chemicals or heavy metals).

The rest of the paper is organized as follows. In Section 2 we briefly discuss 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. 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.

In the current agricultural economic literature, nutrients are usually modeled as flow variables. The material balance accounting provides an estimated surplus or deficit of a nutrient in a given year, but it completely ignores the accumulation of nutrients over time. Although the metrical balance accounting is often justified by referring to the law of mass conservation, ignoring the time dimension is not a harmless simplification. Whether one is interested in nutrients from the point of view of production or pollution, it is important to take the accumulation of nutrient stock into account. We will develop a dynamic model of material balance accounting in the next section. But first, let us present some stylized facts about the nutrient cycle.

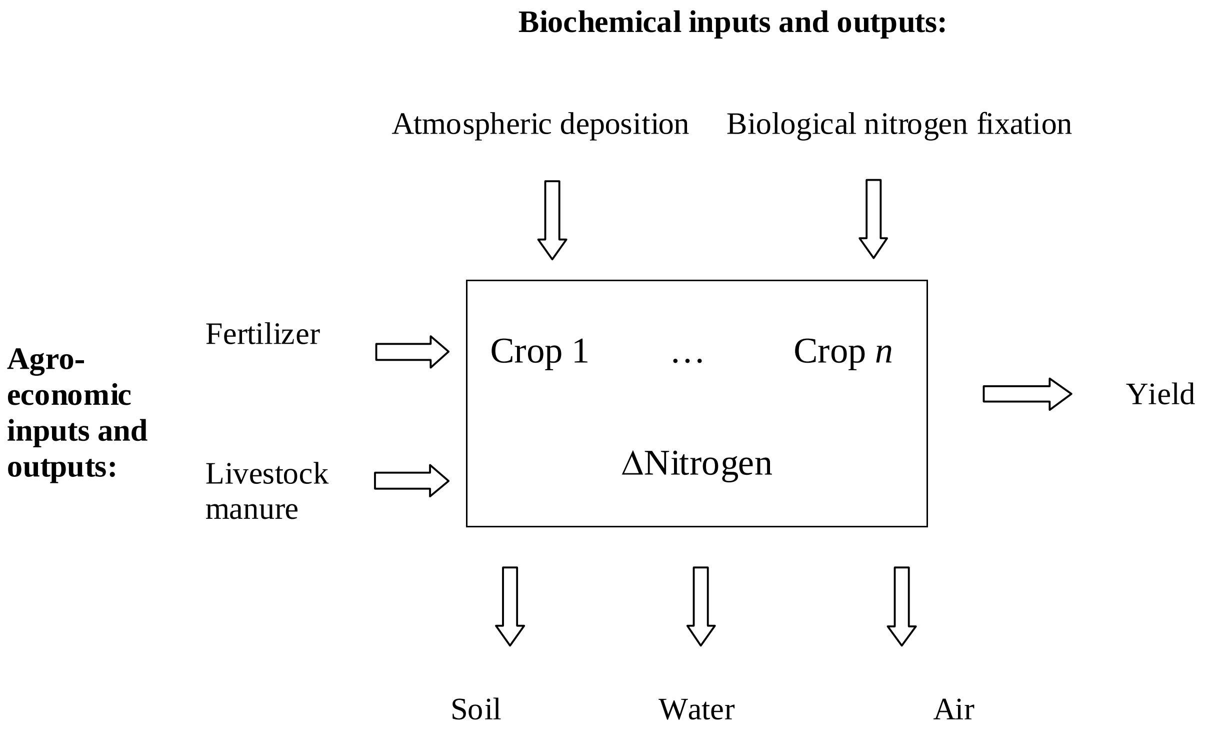

Figure 1: Conceptual model of the nitrogen cycle.

Figure 1 presents a conceptual illustration of the nitrogen cycle (similar illustrations can be found, e.g., in Boyer and Howarth, 2002; and Mosier *et al*., 2004). The main agro-economic inputs of nitrogen are fertilizers and manure. The environmental inputs of nitrogen include atmospheric deposition and biological fixation. A portion of the nitrogen available in the soil is extracted in the harvested crop, which forms the main economic output of nitrogen. Other portions of nitrogen are removed by vertical water movement (runoff), by water flowing through the soil surface (leaching), and by evaporation to air. The main environmental outputs of nitrogen include emissions to water systems, air, and the soil. Nitrogen accumulates as stock pollutant in water, air, and soil, causing damage in water systems in particular. As noted above, we consider the part of the nitrogen stock that is available to plants as production input, and the unavailable part as pollution. The sum of these two stocks is the total nitrogen stock in soil.

The pollution stocks tend to decay gradually over time, as pollution is converted into relatively harmless elements or compounds. The decay rate indicates the proportion of the stock that degenerates within a given period (for example, a year). In the case of nutrient stocks, decay can occur through volatilization and denitrification to air, leaching to ground water, and runoff to surface water, respectively. The remaining nutrient stock carries over to the next period.

In contrast to the static model of mass conservation, the quantity of nutrient entering the system does not always have to be equal to the quantity of nutrient that exits the system. In other words, there can be nutrient surplus or deficit (denoted as ΔNintrogen in Figure 1) in any period of time. This means that the nutrient cycle, such as the one displayed in Figure 1, is not necessarily in its steady state equilibrium. Surplus of nutrient implies that the stock of nutrient increases to the next period, whereas nutrient deficit implies decrease in the stock.

The phosphorus cycle is similar to the nitrogen cycle described in Figure 1. However, the phosphorus cycle lacks the atmospheric phase, and it is considered as one of the slowest biochemical cycles with a low decay rate (e.g., Stevenson and Cole, 1999; Sims and Sharpley, 2005). Phosphorus exists in different forms in the soil, which can be classified to four general groups: plant available inorganic phosphorus, and three forms which are not plant available: organic, adsorbed and primary mineral phosphorus. Available phosphorus determines the total plant available phosphorus pool and phosphorus immediately usable by plants. The main source for phosphorus pollution of surface water is surface runoff. Leaching of phosphorus is generally considered to be limited. The slow biochemical cycle of phosphorus implies that the dynamic modeling of the stock is particularly relevant in the case of phosphorus.

In the next section, we introduce a general model of material balance in the dynamic setting, following the rationale of the standard capital accumulation model in production economics. We then apply it to modeling of nutrient stocks.

3. Dynamic material balance accounting

3.1. General model

For sake of generality, we first consider an arbitrary substance (e.g., a nutrient, heavy metal, or other pollutant), denoting its quantity by z. For clarity, we denote the flow of substance by the lowercase z, and the stock of substance by the capital Z.

Following the seminal article by Ayres and Kneese (1969), the conventional material balance equation is usually presented in the linear form as the difference between the total quantity of z in the inputs and the total quantity of z in the outputs, formally:

(1) $$z = \mathbf{a}'\mathbf{x} - \mathbf{b}'\mathbf{y},$$

where z is a flow variable, $\mathbf{x}$ and $\mathbf{y}$ are the vectors of input and output flows, $\mathbf{a}$ and $\mathbf{b}$ are non-negative vectors that represent the content of substance in the inputs and outputs. Georgescu-Roegen (1986), Daly (1997), Baumgärter (2004), Ebert and Welsch (2007), and Førsund (2009) argue that production follows the laws of thermodynamics, and thus the production processes must obey the conservation of material inputs and outputs. Pethig (2006) proposes a nonlinear model of material balance. However, equation (1) is essentially a static model; it ignores time and is hence applicable to flow pollutants.

A dynamic model of material balance can be stated in the discrete, linear setting as follows:

(2) $Z_t = (1-\delta) Z_{t-1} + \mathbf{a}'\mathbf{x}_t - \mathbf{b}'\mathbf{y}_t$,

where, Z_t and Z_{t-1} represent the stock of substance (*z*) in time periods *t* and *t*-1, respectively, $\mathbf{x}_t$ and $\mathbf{y}_t$ are vectors of inputs and outputs in period *t*, and $\delta \in [0,1]$ is the decay rate.[2] Of course, the model could be stated in the continuous time and/or in nonlinear form, but for practical convenience, we restrict to the discrete time linear formulation in this paper: the observed data of nutrient inputs and outputs comes in the discrete form and the estimates of coefficients **a** and **b** are available. Note the similarity of the dynamic model (2) with the model of capital stock accumulation used in production economics. In that context, Z_t represents the capital stock in period *t*, δ is the depreciation rate, $\mathbf{x}_t$ is a vector of new capital goods installed in period *t*, $\mathbf{y}_t$ is a vector of capital goods sold or scrapped in period *t*, and **a** and **b** are price vectors of capital goods. Thus, $\mathbf{a}'\mathbf{x}_t$ is the total investment in period *t*.

Suppose the true material balance equation of substance *z* is dynamic, that is, equation (2) applies. The use of the static model (1) then implies that surplus *z* in (1) is actually the change of stock between two periods plus decay in period *t*:

(3) $z_t = \mathbf{a}'\mathbf{x}_t - \mathbf{b}'\mathbf{y}_t = Z_t - (1-\delta) Z_{t-1} = (Z_t - Z_{t-1}) + \delta Z_{t-1}$.

We can interpret $Z_t - Z_{t-1}$ as the change of the stock from period *t*-1 to *t*. The second component δZ_{t-1} represents the decay of the stock in period *t*-1. In general, the use of the static material

[2] The decay rate is also referred to as the degradation rate or depreciation rate in the literature.

balance equation (1) in the dynamic context results as a sum of two separate components (change of the stock plus decay), which does not have any natural interpretation.

Consider next the two extreme special cases: a perfectly persistent pollutant with no decay (δ = 0) and a pollutant with instantaneous decay (δ = 1). In the case of a perfectly persistent pollutant, equation (3) reduces to:

(4) $\mathbf{a}'\mathbf{x}_t - \mathbf{b}'\mathbf{y}_t = Z_t - Z_{t-1}$,

which is the change in the stock. Hence, for a perfectly persistent pollutant, surplus z has a meaningful interpretation. In the opposite extreme of instantaneous decay, we have:

(5) $\mathbf{a}'\mathbf{x}_t - \mathbf{b}'\mathbf{y}_t = Z_t$,

Thus, for a pollutant with high decay rate, surplus z equals the level of stock in last period, and hence, such pollutant can be correctly modeled as a flow rather than a stock pollutant. These examples illustrate that the dynamic model reduces to the static model only under some rather restrictive conditions.

3.2. Modeling nutrient stocks

We next apply the insights of the previous sub-section to modeling of nutrient stocks. Note that we can rewrite our general dynamic equation (2) as:

(6) $Z_t = (1-\delta) Z_{t-1} + h_t$,

where $h_t = \mathbf{a}'\mathbf{x}_t - \mathbf{b}'\mathbf{y}_t$ can be interpreted as the *nutrient balance*; the difference between the total nutrients in the inputs and the total nutrients in the outputs in period t. Note that the nutrient balance is essentially a flow variable. Applying the methodology of nutrient balances of the OECD and Eurostat (OECD 2007a, 2007b), nutrient flow h_t for period t can be written as:

(7) $h_t = (FR_t + LM_t + BF_t + AD_t) - (MC_t + NC_t)$,

where, FR_t is fertilizer, LM_t is livestock manure, BF_t is biological fixation and AD_t is atmospheric deposition. On the output side, nutrient is removed from the soil by harvested marketed crops MC_t and non-marketed fodder crops NC_t. Nutrient flow h_t obtained by (7) results into nutrient surplus or deficit measure.

In order to calculate nutrient stock series (6), we need three pieces of information: a time series on the flow of nutrient, an assumption on the decay rate δ and an estimate of the initial nutrient stock level Z_0. The initial nutrient stock is typically unknown, and therefore needs to be estimated. In production economics, the perpetual inventory method is the standard approach to calculate the initial capital stock (see, e.g., Hall and Jones 1999). Assuming a constant growth of nutrient the initial stock is obtained using the sum of an infinite geometric series as:

(8) $$Z_0 = \frac{h_0}{\delta + g_h} ,$$

where Z_0 is the initial stock of nutrient, h_0 is the flow level of nutrient in the initial period, δ represents the decay rate, and g_h is the average rate of growth in nutrient flow levels.

In the context of nutrient pollutant, the decay rate δ has an appealing environmental interpretation. It represents a proportion of the stock which decays in each period due to leaching and runoff of nutrients to water, and volatilization and denitrification to air. Hence, it can be calculated as the sum of the leaching rate, runoff rate, volatilization rate, and denitrification rate. Similar to the coefficients **a** and **b**, different nutrients have different decay rates. The decay rates will generally depend on the soil type, elevation, climatic conditions, and other factors. At the aggregate level of countries, it can be useful to apply the average decay rates approximated based on the available empirical evidence and calibrated based on the observed time series of nutrient flows. Given (7) and (8), and having a meaningful proxy for the decay rate, we are equipped to calculate the nutrient stocks.

4. Stocks and flows of nutrients in the Finnish agriculture

4.1 Objectives

This section presents the results of the dynamic model of material balance accounting for the two main nutrients in agriculture, nitrogen and phosphorus. Due to the data availability and our previous experience, we choose Finland as our case country. The time horizon of this study spans the years 1961 – 2009. Firstly, we calculate the nutrient flow series using average country data of agricultural inputs and outputs and following the OECD manual of nutrient balance calculations (OECD, 2007a, 2007b). We next compute the nutrient stock series by applying our theoretical model introduced in Section 3.

The objectives of this application are twofold. First, we show that it is possible to estimate the nutrient flows and stocks using the readily available data. Second, we aim to illustrate the benefits of the dynamic modeling of nutrient stocks. The dynamic model enables us to analyze the development of the nutrient stock over time. We can also decompose the decay of stock to its components, such as leaching and runoff to water, and evaporation to air, which provides more detailed information of nutrient emissions to water and air.

4.2 Data

Data of the input $\mathbf{x}$ and output $\mathbf{y}$ quantities, namely fertilizers, livestock, land use, and crop yield, were obtained from the FAO statistical databases (FAOSTAT) and the Eurostat databases. More specifically, data on the total quantities of nitrogen and phosphorus from fertilizers (in tons) are only available for the period 1985 – 2009 from Eurostat. The total fertilizer consumption (in tons) is available from FAOSTAT for the period 1961 – 2002. The quantities of nitrogen and phosphorus for the missing time periods were estimated by approximating the portion of these nutrients contained in total fertilizer consumption.

The coefficients of nitrogen and phosphorus contents in outputs and inputs were obtained from the OECD statistical extracts (OECD, 2008). The manure nutrient quantities (in tons) were calculated by multiplying the heads of livestock (obtained from FAOSTAT) by the nutrient coefficients of OECD. The atmospheric deposition of nutrients were calculated based on the data on the utilized agricultural area (UAA, in ha) obtained from FAOSTAT. Nutrient uptake by crops and forage (in tons) were calculated by multiplying quantity of harvested crop and forage (obtained from FAOSTAT) by the conversion coefficients of OECD. Having the quantities of nutrients in inputs and output, we calculated the flow series for nitrogen and phosphorus. Finally, we confirmed that our nutrient flows are consistent with the nutrient balances reported for Finland by the OECD (2008).

We next constructed the stocks of nitrogen and phosphorus. We must acknowledge that the average decay rates of nutrients are difficult to estimate, as the rates are affected by several factors such as the timing and the method of fertilizer application, the soil type, and rainfall, among other factors. The decay rates used in this study are specified based on the empirical evidence reported in the literature (e.g., Stevenson, 1982; Brady and Weil, 1999; Zhou *et al*., 2004) and our own calculations. Further research would be needed to obtain more reliable and precise decay rates. However, we believe the dynamic modeling of nutrient stocks is useful despite the uncertainty about the exact decay rates. In production economics, there is similar uncertainty about the appropriate depreciation rates for the capital inputs that are used for estimating the capital stock.

The decay rate of nitrogen is specified as follows. Zhou *et al*. (2004) find that the nitrogen leaching rate in a sandy loam soil ranges between 16.2 and 30.45 percent and in a clay loam soil between 5.7 and 9.6 percent of the total nitrogen added. For the Finnish agricultural soils, we assume the nitrogen leaching rate is 20 percent of the stock. We specify the denitrification rate as 9 percent and the volatilization rate as 2.2 percent of the nitrogen stock, based on our own calculations and empirical findings reported in the literature.

Unlike nitrogen, phosphorus is much less soluble in water and it leaches from the soil at a much slower rate. The phosphorus loss is mainly due to surface runoff and is estimated as less than 5 percent of the available phosphorus stock (Sharpley *et al*., 1995a, 1995b). In this study, we specify the combined rate of leaching and runoff as 5 percent. The next subsection presents a comparative analysis of the flow and stock estimates for nitrogen and phosphorus.

4.3 Nitrogen flows and stocks

The development of the estimated nitrogen flows and stocks is illustrated in Figure 2 and Table 1. Figure 2 presents the nitrogen flow [red curve], calculated using the static material balance equation, and the nitrogen stock [black curve], calculated using the dynamic material balance equation, for the years 1961 – 2009, expressed in kg of N per ha of UAA. To provide a complementary view, Table 1 presents the annual averages calculates for the five decades between 1961 and 2009, itemizing the main inputs and output flows of nitrogen.

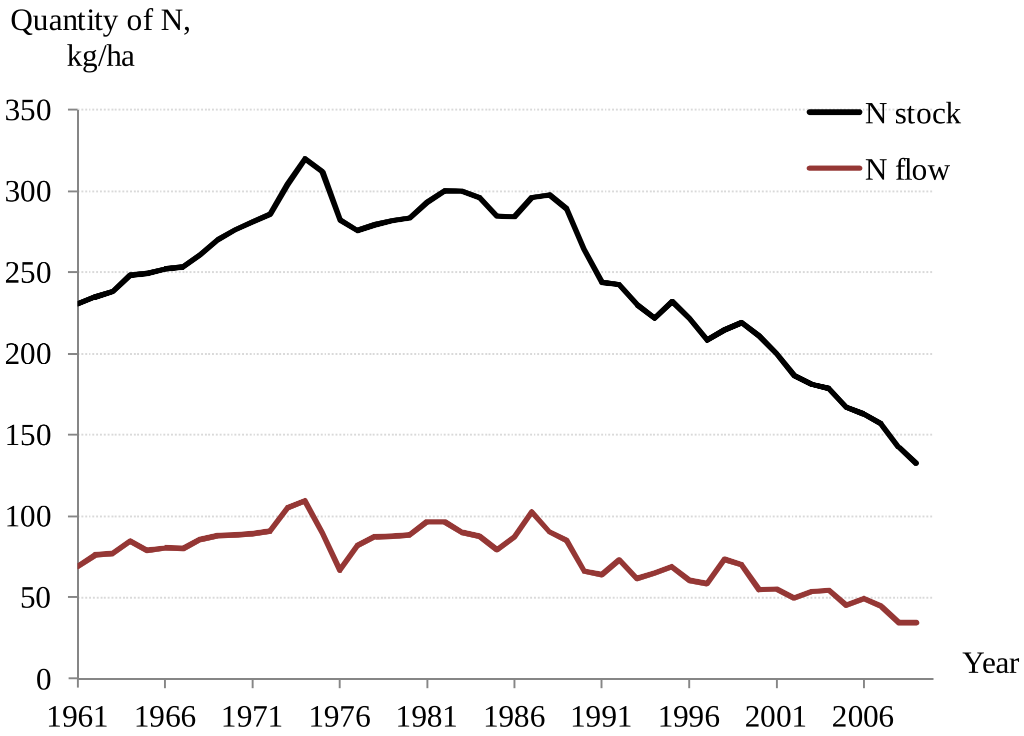

Figure 2: Nitrogen stocks and flows in the years 1961 – 2009; in kg of N per ha of UAA.

Figure 2 reveals an interesting pattern in the stock of nitrogen. The nitrogen stock increased until the early 1970s, until the first oil crisis in 1973. After a sharp drop in 1975 – 1976, the nitrogen stock remained relatively stable until the early 1990s. Since then, the nitrogen stock has decreased considerably as a result of more stringent environmental policy. Finland joined the EU in 1995, and since then, the EU agricultural policy has been applied.

The development of the nitrogen flow follows a similar pattern as the stock. Indeed, as the decay rate of nitrogen is specified as 31.2 percent, the nitrogen stock is approximately three times larger than the annual flow of nitrogen.

Table 1: Average annual nitrogen flows and stock in the decades between 1961 and 2009

	Period				
Flows and stock	1961-1970	1971-1980	1981-1990	1991-2000	2001-2009

Inputs:					
Fertilizer, tN	141 956	212 110	217 562	176 300	155 447
Livestock manure, tN	130 613	106 959	90 876	70 886	61 933
Other inputs, tN	25 239	24 053	22 384	21 848	21 066
Output:					
Harvested crops, tN	73 200	108 794	116 994	117 864	132 687
Flow, tN	224 608	234 329	213 828	151 169	105 759
Flow, kgN/ha	80.8	89.6	88.1	65.0	46.7
Stock, kgN/ha	251.4	290.5	290.5	224.4	167.5

Table 1 illustrates the development depicted in Figure 2 from another angle. This table partitions the time horizon to five decades using the average values of the annual figures for each variable reported in the table. While some information is lost in the aggregation, the table allows us to attribute the flow of nitrogen to specific inputs and outputs. Fertilizers accounted on average for about 60 percent of the nitrogen input between 1961 and 2009. The share of livestock manure in total nitrogen inputs was on average 30 percent. Atmospheric deposition, the fixation of nitrogen by leguminous crops and free living organisms contributed on average 8 percent to total nitrogen input. Table 1 also reveals that the decrease of the nitrogen flow has occurred both through the decrease in the amounts of fertilizer, livestock manure, and other inputs, but also through the simultaneous increase in the uptake of nitrogen in the harvested crop.

We next compare the decay of nitrogen stock and its components to the nitrogen flow. Figure 3 plots the nitrogen flow (i.e., the static material balance) [red curve], the decay of nitrogen stock calculated using the dynamic model [grey curve], and the subcomponents of decay that represent the leaching and runoff to water systems [dark blue curve], and evaporation to air [light blue curve], respectively. We find that the changes in the nitrogen stock (the dynamic model) follow very closely the nitrogen flow calculated using the static material balance. However, the decay of the nitrogen stock according to the dynamic model is much more stable over time than the flow of nitrogen according to the static material balance.

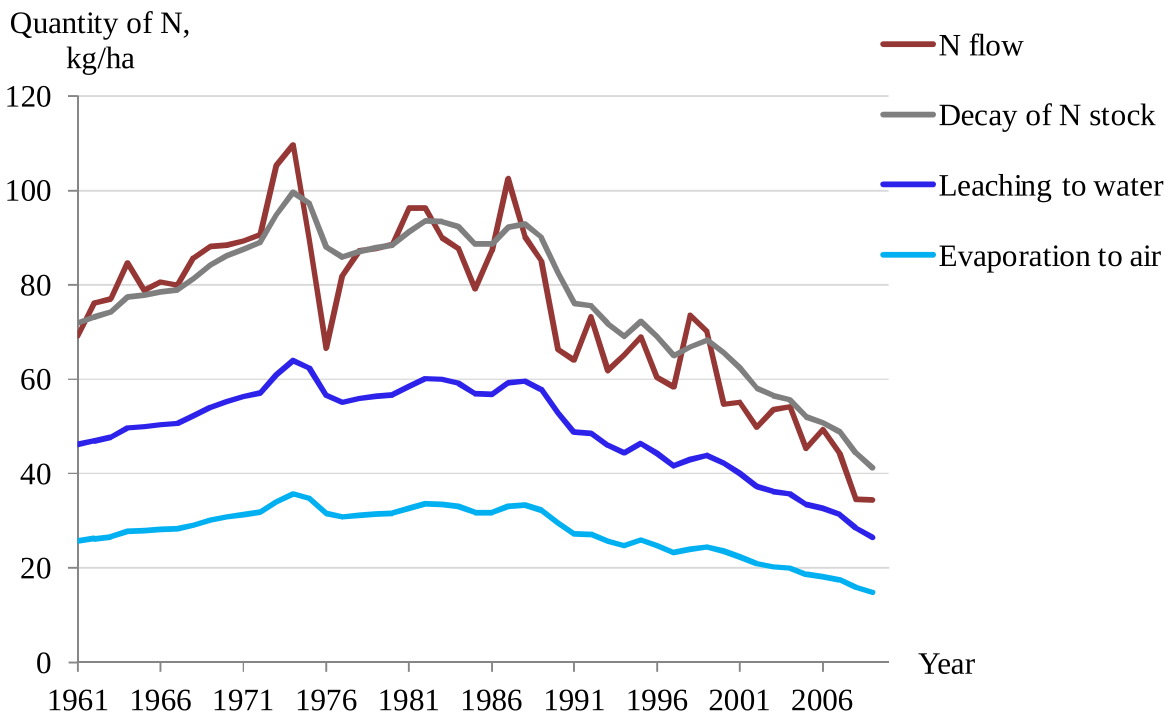

Figure 3: Nitrogen flow and stock decay; leaching, volatilization and denitrification of nitrogen in 1961 – 2009; in kg of N per ha of UAA.

Large annual fluctuations in the nitrogen flow may be problematic for the use of the material balance as an indicator of environmental performance or eco-efficiency in static cross-country comparisons that consider a single year (or a few years) only. The decay of nitrogen stock provides a more stable indicator for cross-country comparisons. Further, Figure 3 illustrates that the nitrogen flow may overestimate the environmental pressure in periods where the nitrogen stock is increasing (the N flow exceeds the decay of N stock in the years 1961 –

1975), whereas the nitrogen flow tends to underestimate the environmental pressure when the nitrogen stock decreases (the N flow is lower than the decay of N stock in the years 1998 – 2009). This is because the nitrogen stock adjusts to the changes in the nitrogen flow with considerable delay. We next consider the case of prosphorus, which has a very slow biochemical cycle.

4.4 Phosphorus flow and stock

Similar to the previous section, we first describe the phosphorus flow and stock in the years 1961 – 2009 in Figure 4. Table 2 provides a complementary view by reporting the phosphorus flows and stocks, the main inputs and output of phosphorus, averaged over the five decades within the time horizon considered.

The development of the phosphorus stock depicted in Figure 4 is quite similar to the pattern of the nitrogen stock illustrated in Figure 2. The increase of the phosphorus stock continued until the late 1980s, but the subsequent decrease of the phosphorus stock has been quite dramatic. In 2009, the total phosphorus stock was less than 70 percent of its maximum value in 1987.

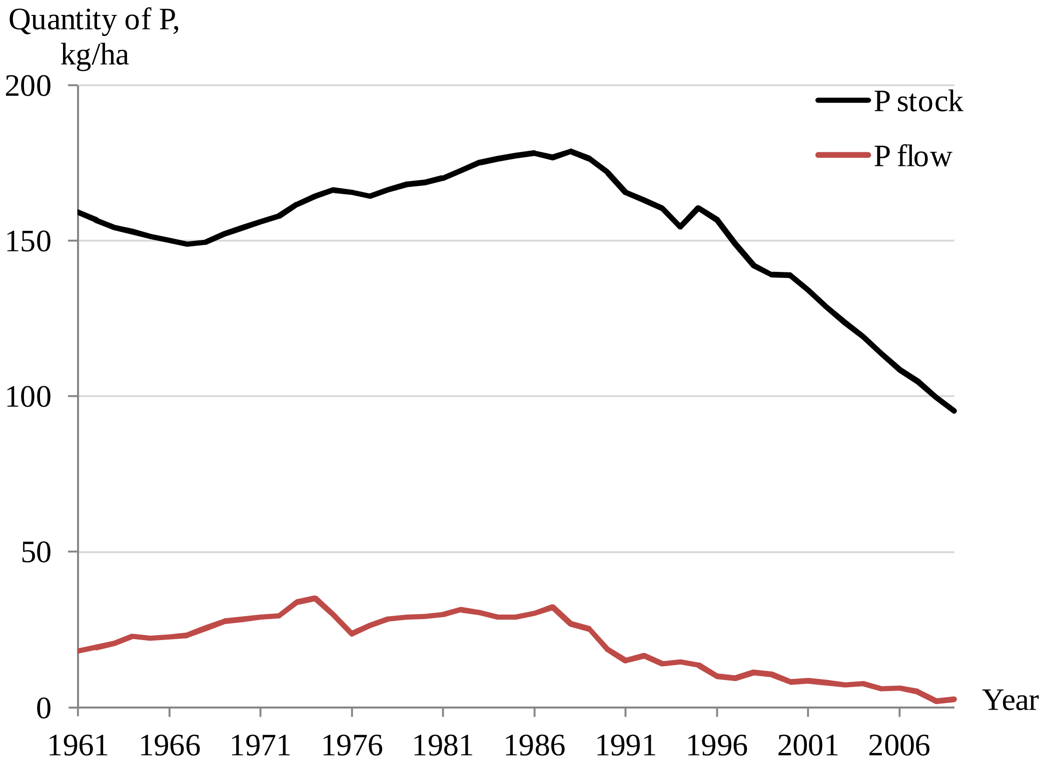

Figure 4: Phosphorus stocks and flows in 1961 – 2009; in kg of P per ha of UAA.

Table 2: Average annual phosphorus flows and stock in the decades between 1961 and 2009

	Period				
Flows and stock	1961-1970	1971-1980	1981-1990	1991-2000	2001-2009
Inputs:					
Fertilizer, tP	48 286	68 452	64 755	29 079	18 120
Livestock manure, tP	26 837	25 667	22 757	18 813	16 950
Other inputs, tP	1 251	1 176	1 092	1 045	1 021
Output:					
Harvested crops, tP	12 380	18 500	19 933	20 062	22 604
Flow, tP	63 993	76 794	68 670	28 874	13 487
Flow, kgP/ha	23.0	29.4	28.3	12.4	6.0
Stock, kgP/ha	152.9	163.9	175.3	153.0	116.6

Table 2 allows us to assess the sources of phosphorus in more detail. Similar to the case of nitrogen, fertilizers accounted for about 63 percent of the total phosphorus input. The share of livestock manure in total phosphorus inputs was on average 35 percent. The share of other inputs contributed only 2 percent of the total phosphorus input. The total input of phosphorus was on average four times larger than the phosphorus uptake by harvested crop and forage. Table 2 illustrates that the output of phosphorus in harvested crop has increased at relatively steady rate. However, the sharp decline in the phosphorus flow in Finland is mainly thanks to the dramatic decrease in the phosphorus input from fertilizers in the past two decades.

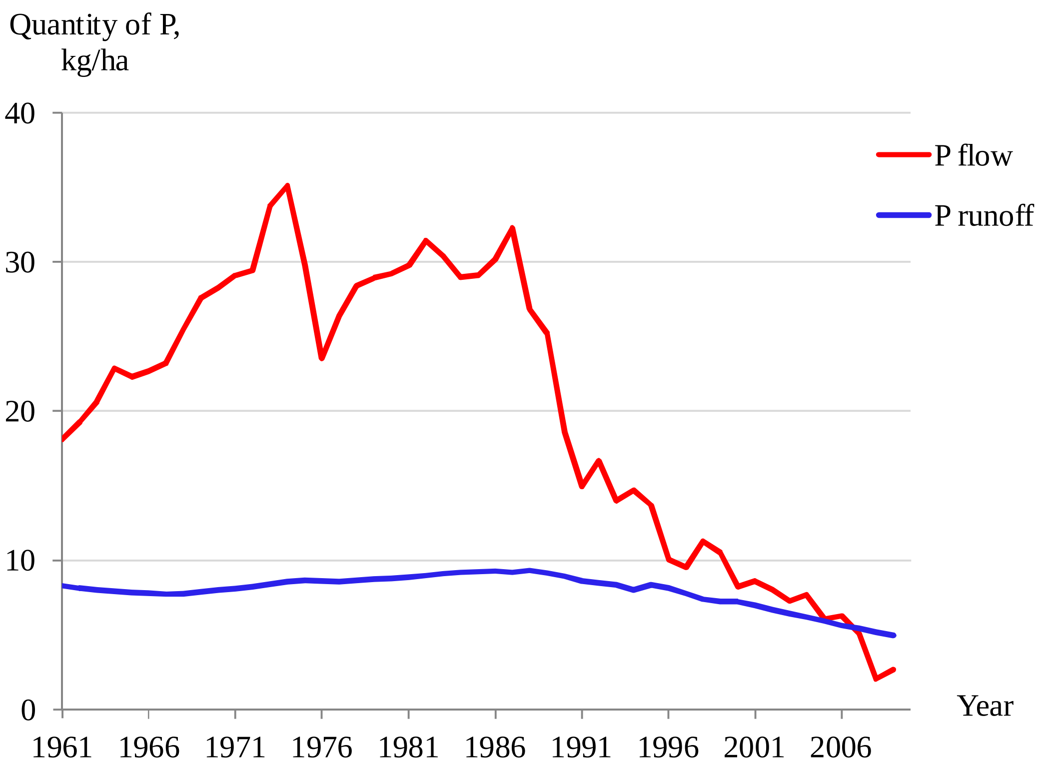

Figure 5: Phosphorus flows and runoff of phosphorus in 1961 – 2009; in kg of P per ha of UAA.

Figure 5 compares the phosphorus flow [red curve] calculated using the static material balance equation and the decay of phosphorus stock [blue curve] calculated using the dynamic model. In the case of phosphorus, the decay occurs almost solely as a result of runoff to surface waters; leaching to ground water and the atmospheric evaporation are considered to be negligible.

Figure 5 illustrates that the use of a static versus dynamic model can provide a different picture on the pollution problem. Based on the phosphorus flow calculated using the static material balance equation, it appears that the phosphorus emissions increased dramatically during the 1960s, followed by a radical decrease of phosphorus emissions since the late 1980s. However, the dynamic model of phosphorus stock suggests that the quantities of phosphorus runoff have not fluctuated as dramatically as the static nutrient balance accounting suggests. This is due to the fact that phosphorus has a very slow biochemical cycle, and hence the phosphorus stock responses to the changes in the flow of phosphorus with a considerable delay. This is evident from Figure 5: the sharp increase of the phosphorus flow in the 1960s resulted as gradual but rather moderate increase in the phosphorus runoff estimates obtained by using the dynamic model. Unfortunately, the sharp decrease of the phosphorus flow in the past decades does not help to improve the environmental quality immediately: the runoff of phosphorus accumulated in the soil will continue for years to come. In the most recent years, the runoff of phosphorus from the stock far exceeds the annual phosphorus input.

5. Conclusions

We have critically examined the conventional approach to material balance accounting as applied to nutrients in agricultural production. Our main thesis is straightforward. We argue that the conventional static models that ignore the accumulation of nutrients to soil, water and air overlook an important dimension of the nutrient cycle: the time. We proposed a dynamic model of material balance accounting which is generally applicable to any stock pollutants. We then applied the proposed dynamic model to the cases of the two main nutrients, nitrogen and phosphorus. Using empirical data of Finland, we estimated the flows and stocks of nitrogen and phosphorus for the years 1961 – 2009. The empirical study shows that it is possible to construct meaningful estimates of the nutrient stocks at the aggregate level of a country using the information and data that are readily available. In our view, the empirical study also demonstrates that dynamic modeling can provide useful information and insights beyond the conventional material balance accounts. For example, we found the decay of nutrients to be considerably more stable over time than the annual surplus of nutrients would suggest.

Appropriate modeling of the flow and stock variables, and the delayed response of the stock to the changes in the flow variables, are critically important issues from the point of view of environmental policy. The dynamic model of material balance proposed in this paper is not restricted to the nutrient pollution from agriculture. In fact, most pollutants accumulate in the environment, including the green-house gases, heavy metals, and toxic chemicals. We hope our study could inspire more realistic modeling of material balance accounts in other application areas as well. One promising application area is productivity and efficiency analysis, where the material balance principle has recently attracted considerable attention and debate (e.g., Coelli *et al*. 2007; Lauwers, 2009). We believe the dynamic material balance equation could provide more meaningful and useful input-output data for the purposes of environmental performance or eco-efficiency analysis within the paradigm of productive efficiency analysis.

There are several interesting avenues of future research also in the context of agriculture. It would be interesting to extend the empirical study presented in this paper to cover other countries for which data are available. Further, it would be interesting but more challenging to estimate nutrient stocks at the disaggregate levels of individual farms or regions. However, a lot of further work is needed in order to calibrate the nutrient coefficients and the decay rates to take into account the specific regional conditions such as the soil type, elevation, and climatic conditions. More detailed understanding of the nutrient cycle at the regional levels could help to target the environmental policy measures more efficiently across different regions.

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