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Applying insights from production theory and frontier estimation to sustainability assessment in agriculture

Doctoral Dissertation

Natalia Kuosmanen

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Applying insights from production theory and frontier estimation to sustainability assessment in agriculture

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Abstract

Sustainability is a multidimensional concept that encompasses environmental, social and economic dimensions. A large number of qualitative concepts and definitions of sustainability have been suggested. However, quantifying the notion of sustainability as an operational measure has proved challenging due to a variety of meanings attached to this concept. The aim of this dissertation is to contribute to quantitative assessment of sustainability, focusing on agriculture. The thesis consists of an introductory part and five articles, which approach the assessment of sustainability from different angles.

The main objective of the first three studies is to develop a general framework for sustainability assessment at different levels of aggregation. The first study demonstrates the critical importance of separating the conceptual definition of sustainability from the questions concerning its empirical assessment. The following two articles apply the generalized framework proposed in the first article to sustainability assessment at farm and sector levels. The proposed approach utilizes existing methods of frontier estimation that are applied for productivity and efficiency analysis. Apart from the conventional nonparametric Data Envelopment Analysis (DEA) and parametric Stochastic Frontier Analysis (SFA), a recently developed Stochastic Nonparametric Envelopment of Data (StoNED) approach, is applied in this thesis.

The last two articles of the thesis focus on a specific measurement issue within sustainability assessment: how to measure nutrient emissions from agriculture to water, soil, and air. Analyzing stocks and flows of nutrients requires dynamic modeling. The fourth article proposes a new dynamic approach to model the nutrient stocks and flows and demonstrates the advantages of the proposed dynamic model over the conventional static approaches to material balance accounting. The empirical applicability and usefulness of the dynamic model are demonstrated through an empirical application to Finnish agricultural sector where the stocks and flows of nitrogen and phosphorus are estimated for a 48-year period. In the fifth article, the analysis is extended to cover 14 European countries in years 1961–2009. The proposed dynamic material balance approach allows one to analyze the development of nutrient stock over time and decompose the nutrient flows to water, air and soil. The stocks and flows calculated using the dynamic model can be readily utilized in sustainability assessment as indicators of environmental pressure. Apart from the theoretical contribution, last two articles of the thesis open up interesting new avenues for future research; for example, disaggregating nutrient stocks and flows to the level of individual farms or regions presents an interesting but challenging research problem.

Key words:
frontier methods, efficiency analysis, sustainability assessment, agriculture

Tuotantoteorian ja rintamaestimoinnin menetelmien soveltaminen maatalouden ekologisen kestävyyden arvioinnissa

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Tiivistelmä

Ekologinen kestävyys on moniulotteinen käsite, joka sisältää ympäristöä, yhteiskuntaa ja taloutta koskevia ulottuvuuksia. Kestävyydelle on ehdotettu lukuisia erilaisia määritelmiä. Siitä huolimatta ekologisen kestävyyden soveltaminen konkreettisiksi käytännön toimenpiteiksi on osoittautunut haastavaksi useista eri syistä. Tämän väitöskirjan tavoitteena on edistää ekologisen kestävyyden kvantitatiivista arviointia keskittyen erityisesti maatalouteen. Väitöskirja koostuu johdannosta sekä viidestä artikkelista, jotka lähestyvät ekologisen kestävyyden arviointia eri näkökulmista.

Kolmen ensimmäisen tutkimuksen pääasiallisena tavoitteena on kehittää yleinen menetelmä ekologisen kestävyyden arviointiin. Ensimmäinen artikkeli havainnollistaa miksi on tärkeätä erottaa selkeästi ekologisen kestävyyden käsitteellinen määritelmä sen empiiristä soveltamista koskevista kysymyksistä. Seuraavat kaksi artikkelia puolestaan osoittavat ensimmäisessä artikkelissa ehdotetun yleisemmän menetelmän käytettävyyttä ekologisen kestävyyden arvioinnissa eri tuotantotasoilla. Ehdotettu menetelmä hyödyntää jo olemassa olevia rintamaestimoinnin menetelmiä, kuten ei-parametriset DEA-menetelmä (*Data Envelopment Analysis*) ja parametrinen SFA-menetelmä (*Stochastic Frontier Analysis*). Niiden lisäksi tutkimuksessa sovelletaan äskettäin kehitettyä StoNED-menetelmää (*Stochastic Nonparametric Envelpoment of Data*).

Viimeiset artikkelit pureutuvat maatalouden ravinnepäästöihin ekologisen kestävyyden näkökulmasta. Artikkeleissa esitetään uusi dynaaminen malli maaperässä olevien ravinnevarantojen sekä ilmakehään ja vesistöihin kohdistuvien ravinnevirtausten analysointia varten. Tutkimuksessa osoitetaan dynaamisen mallin edut perinteisiin staattisiin materiaalitaselaskelmiin perustuviin malleihin verrattuna. Dynaamisen mallin hyödyllisyyttä ja sovellettavuutta havainnollistetaan neljännessä artikkelissa arvioimalla Suomen maatalouden typen ja fosforin varannot sekä niiden virtaukset 48-vuotisella ajanjaksolla. Viidennessä artikkelissa tarkastelu laajennetaan kattamaan neljätoista Euroopan maata ajanjaksolla 1961–2009. Ehdotettu dynaaminen malli mahdollistaa ravinnepäästöjen aikaisempaa tarkemman kohdentamisen maaperään, ilmakehään ja vesistöihin kohdistuviksi ravinnevirroiksi. Dynaamisen mallin avulla lasketut ravinnevarannot ja -virrat ovat suoraan hyödynnettävissä ekologisen kestävyyden arvionnissa ympäristökuormituksen indikaattoreina. Teoreettisten hyötyjen lisäksi kahdessa viimeisessä artikkelissa esitetty dynaaminen mallinnustapa avaa monia uusia tutkimusmahdollisuuksia: esimerkiksi ravinnevarantojen ja -virtausten alueellinen kohdentaminen yksittäisille maatiloille tai alueille on mielenkiintoinen mutta haastava jatkotutkimuksen aihe.

Avainsanat:
ekologisen kestävyyden arviointi, maatalous, rintamaestimointi, tehokkuusanalyysi

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List of articles

The thesis is based on the following articles, which are referred to by their Roman numerals I–V:

I. Kuosmanen, T. & Kuosmanen, N. 2009. How not to measure sustainable value (and how one might)? *Ecological Economics* 69, 235–243. (© Copyright of Elsevier Science)

II. Kuosmanen, T. & Kuosmanen, N. 2009. Role of benchmark technology in sustainable value analysis: An application to Finnish dairy farms. *Agricultural and Food Science* 18, 3025–316. (© Copyright of Agricultural and Food Science)

III. Kuosmanen, N., Kuosmanen, T. & Sipiläinen, T. 2013. Consistent aggregation of generalized sustainable values from the firm level to sectoral, regional or industry levels. *Sustainability* 5, 1568–1576. (© 2013 by the authors; licensee MDPI, Basel, Switzerland)

IV. Kuosmanen, N. & Kuosmanen, T. 2013. Modeling cumulative effects of nutrient surpluses in agriculture: A dynamic approach to material balance accounting. *Ecological Economics* 90, 159–167. (© Copyright of Elsevier Science)

V. Kuosmanen, N. 2013. Estimating stocks and flows of nitrogen: Application of dynamic nutrient balance to European agriculture. Submitted for review.

Author's contribution

The first three articles were prepared within the EU FP6 project SVAPPAS (Sustainable Value Analysis of Policy and Performance in the Agricultural Sector) concerning the development and adaptation of a methodology for the assessment of sustainability performance and policies in agriculture. The work was carried out at MTT Economic Research during the years 2007 to 2009.

Article I is a joint work with Timo Kuosmanen. Natalia Kuosmanen's contribution was the data collection and processing for the reinvestigation of the empirical study of European manufacturing firms, writing a code for simulations using MATLAB technical computing program and performing the Monte Carlo study, and contributing to the writing of the article.

In Article II, the data collection and the empirical part was performed by Natalia Kuosmanen, while the theoretical review of the alternative methods to estimation the benchmark technologies was performed by Timo Kuosmanen. Both authors contributed equally to writing the paper.

In Article III, the data collection, performing the empirical analysis and writing of the paper has mainly been performed by Natalia Kuosmanen. The theoretical part of this article was developed together with Timo Kuosmanen and Timo Sipiläinen.

The idea of Article IV emerged in summer 2012 at the time of another joint work with Timo Kuosmanen in relation to assessment of environmental performance of agriculture. While, the theoretical part of this article was developed together with Timo Kuosmanen, Natalia Kuosmanen collected and processed the data, performed the empirical application and wrote the first draft of the paper.

In Article V, Natalia Kuosmanen is the sole author.

Contents

1 Background

1.1 Dimensions of sustainability

The classic paper *Tragedy of Commons* by Hardin (1968) brought the environmental problems to public attention, showing the dependence of human beings on natural resources and their inability to spend them more modestly. Ultimately, the *Tragedy of Commons* says that resources, such as forests, air, water, energy sources among other resources will be exhausted because no one will take responsibility. Later, the influential report *Our Common Future* by the World Commission on Environment and Development (1987), known as the Brundtland report, introduced the notion of sustainable development, but also highlighted two key concepts of sustainability:

> "*the concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs*".

Thus in its original form, the concept of sustainability was mainly associated with maintenance of environmental quality and concerns for the environment in general.

Today sustainability is defined and understood in a variety of ways. It is referred to in many fields, including business, chemistry, economics, engineering, environmental studies, governance, technology, among others. In general, sustainability unites the economic development along friendliness to the environment and taking into account cultural, health–related, and other social aspects (Glavič and Lukman, 2007; Mebratu, 1998; White, 2013).

In general, three core dimensions of sustainability have been recognized: *the economy, the environment*, and *the society*. The first dimension of sustainability addresses the issue of producing goods and services on a continuing basis. The second environmental element concerns stable resource base by avoiding over–exploitation of renewable resources and depleting non–renewable resources. The third social element promotes distributional equity and adequate provision of social services, such as health and education. Thus, sustainability concept is about applying these three dimensions simultaneously (Moldan et al., 2012; Singh et al., 2009).

In the scope of this thesis, we focus on sustainability assessment in agriculture. Similar to the general concept of sustainability, sustainable agriculture is a complex concept that is based on three pillars: economic, environmental and social. One of the common definitions of sustainable agriculture is given by Lewandowski et al. (1999). It states that:

> "*the management and utilization of the agricultural ecosystem in a way that maintains its biological diversity, productivity, regeneration capacity, vitality, and ability to function, so that it can fulfill –today and in the future – significant ecological, economic and social functions at the local, national and global levels and does not harm other ecosystems*". (Lewandowski et al., 1999).

The complexity of the sustainability concept and its multidimensionality makes it challenging to measure. Similar to the environmental performance indicators, measures of agricultural sustainability developed during the previous two to three decades range from oversimplified indicators to more sophisticated ones (see for a review e.g., Bell and Morse, 1999; Olsthoorn et al., 2001; Tyteca, 1996; Callens and Tyteca, 1999; Hayati et al., 2010). As an example, commonly used simple indicators include such measures as yield per hectare, land productivity, resource efficiency, environmental efficiency (calculated as output per unit of environmental bad), and other. Besides simple indicators, more sophisticated methods to assess sustainability performance usually involve simple indicators carrying information about a certain dimension of sustainability (e.g., environmental, social, and/or economic) and use them in various estimation procedures (e.g., frontier estimation and performance assessment).

Further, OECD's strategy for green growth in the food and agriculture sector states the following:

> *Green Growth "seeks to define an economic development path that is consistent with long–run environmental protection, using natural resources within their carrying capacity, while providing acceptable living standards and poverty reduction in all countries*". (OECD, 2011a).

One of the aims of the OECD's Green Growth strategy is to identify and broaden the range of existing indicators that could be used to measure and record progress towards green growth and to allow for comparative analysis and benchmarking of countries on green growth.

Although a large number of indicators and methods have been suggested to measure agricultural sustainability, there is still an increasing need for tools that would allow for objective quantification and measurement of this multidimensional concept at both micro and aggregate levels. To this end, there are at least three areas where this thesis can contribute to the sustainability assessment in agriculture. First, a large number of sustainability indicators available in the literature simply fail to separate its conceptual idea from its operational measure (also called an estimator). Applying such estimators with untested underlying assumptions would most likely lead to wrong and biased conclusions. This needs to be illustrated and clarified. Secondly, there is a need for a measure that would be consistent both at micro and aggregate levels. Third, since agricultural sustainability is rather a dynamic than static concept, there is a call for quantitative approaches that would take dynamics into consideration.

1.2 Objectives of the study

The main objective of this thesis is to develop new approaches to sustainability assessment in agriculture based on the insights from the production theory and frontier estimation. Articles I–III focus on the assessment of sustainability performance of firms at micro and macro levels and are united by the common theme of the sustainable value method. In contrast, Articles IV and V focus on a particular environmental problem – nutrient emissions in agriculture. These two studies depart from the conventional approach of nutrient modeling in agriculture, called nutrient balance approach.

The general aim of the first three articles of this thesis is to improve the existing approaches to measuring sustainability of firms and to eliminate at least some of the limitations of these methods. Thus, the goal is to complement the approaches of sustainability measurement literature. The main objective of Article I is to examine the sustainable value approach, that is one of the promising attempts in the literature of sustainability assessment, for its underlying assumptions. After identifying and discussing the shortcomings of the sustainable value method, our aim is to develop a more general formulation of the sustainable value by applying insights from frontier estimation literature. In fact, the idea is to establish a link between the existing techniques of productive efficiency analysis and the conceptual idea of the sustainable value method, which will enable one to estimate sustainability performance along the lines of the sustainable value approach. To illustrate the possibilities of the generalized sustainable value method, Article II presents an examination of alternative parametric and nonparametric methods for estimating the benchmark technology in the context of the sustainable value analysis. In Article III, our next goal is to develop a systematic approach for aggregating firm level sustainable value indicators to sector, region, or industry levels, which is then illustrated by an empirical application to Finnish dairy and crop sectors.

Articles IV and V approach our main objective of sustainability measurement from slightly different angle. These two studies focus on the nutrient emissions in agriculture starting from the conventional approach of nutrient balance, which estimates the potential environmental pressures from nutrients. In particular, nutrient balance is used as an agri–environmental indicator for the potential nutrient pollution to natural assets, such as water, air, and soil. The aim of Article IV is to address some of the theoretical and practical problems of the nutrient balance approach and to develop a dynamic model of nutrient balance. The proposed dynamic model applies insights from the standard model of capital accumulation used in production economics and establishes a link between capital stocks and investment and nutrient stocks and flows. To illustrate the insights that dynamic modeling can provide beyond the static models of material balance, Article IV applies the dynamic model to estimate nitrogen and phosphorus flows and stocks for the Finnish agricultural sector. The objective of Article V is to elaborate further the theoretical contributions presented in Article IV and to apply the dynamic model to estimation flows and stocks of nitrogen to European agriculture.

2 Methodologies

2.1 Sustainable value

The concept of *sustainable value* was introduced by Figge and Hahn (2004, 2005). In contrast to burden–oriented approaches, where the focus is on the assessment of cost or potential harm of resources use (e.g., Life Cycle Analysis, Eco–Efficiency, Global Reporting Initiative), the sustainable value approach aims to focus on the value created with these resources. According to the original developers, the sustainable value is based on the notion of opportunity cost, where economic, environmental, and social resources are assessed based on their relative value contribution. In other words, a firm is said to create a sustainable value whenever it uses its resources more efficiently than another firm would have used it. In the context of the sustainable value approach, another firm is referred to as the benchmark, which is defined by just a single observation. This should not be confused with interpretation of the benchmark that is used in the literature of frontier estimation (e.g., Färe et al., 1994, 2007). Sustainable value has been applied to empirical assessments of sustainability performance at country level (Ang et al., 2011), across different sectors (Hahn et al., 2007; ADVANCE project 2008) and within specific sectors such as agriculture (Van Passel et al., 2007; Van Passel and Meul, 2012). Besides that, there is also ongoing research on practical aspects of this approach and its combinations with other methods (e.g., Van Passel et al., 2009).

The sustainable value concept is inspired by the constant capital rule and strong sustainability. In order to achieve sustainable development, the constant capital rule (Solow, 1974) imposes the total capital stocks of the economy should not decline over time. In the context of the sustainable value approach it means that reallocating resources from firms that create negative sustainable value to firms that create positive sustainable value should improve economic welfare without affecting the total capital stocks of the economy in any way. Further, strong sustainability assumes non–substitutability of at least some forms of capital, or requires a certain critical level which must be conserved to avoid irreversible losses. In this sense, the relative measure of the sustainable value shows where a higher economic welfare could be achieved without increasing the total resource use of the economy by reallocating resources from firms with negative sustainable value to those with positive value.

I was introduced to the sustainable value paradigm in 2007 when I had started my doctoral studies and was recruited to MTT to work in the SVAPPAS project (Sustainable Value Analysis of Policy and Performance in the Agricultural Sector). This was a unique opportunity for a first–year doctoral student: SVAPPAS was a part of the EU FP6 program, bringing together research groups from different European countries, including Belgium, Germany, United Kingdom, Switzerland, Hungary, Italy and Finland. The general aim of the project was to develop and adapt a methodology for the assessment of sustainability performance and policies in agriculture. Starting with testing one of the promising sustainability indicators in the literature, the sustainable value approach, the task of the research group was to further develop this approach and to test it in country applications at both micro and macro levels.

The basic idea of the sustainable value is interesting. However, together with my supervisors we realized that the practical implementation of this method rests on very restrictive and rather unrealistic assumptions. Our critical comments formed the first article of the thesis. In this article we show that the sustainable value method implicitly assumes linear production technology for evaluated firms, where specific coefficients determined by just a single data point labeled as benchmark. Using the sustainable value as an illustrative example, our aim was to bring to attention of scholars the problems not only limited to the sustainable value approach in particular but also many other sustainability indicators where different dimensions of sustainability are aggregated by simple averaging. By drawing the line between the conceptual idea and the operational measure (estimator), we focused on the implicit properties of the sustainable value estimator and tested its performance in the controlled environment of Monte Carlo simulations. Our results suggested that even under ideal conditions with the data generating process designed to be as favorable as possible to this estimator, the sustainable value performs very poorly.

We presented our findings in several SVAPPAS meetings, which resulted in a discussion between the participants of the project. A comment paper of Figge and Hahn (2009) criticized Article I for a misspecification of the sustainable value approach and tried to justify it with further conceptual discussions. These debates also reflected in the follow–up publications (e.g., Ang and Van Passel, 2010; Mondelaers et al., 2011; Ang et al., 2011). However, the purpose of Article I was not to criticize the theoretical concept of the sustainable value, but rather identify its underlying properties and shortcomings. One of the general objectives of this work was to employ the theoretical concept of the sustainable value with techniques developed in the field of productive efficiency analysis. However, the view of Figge and Hahn in (2009) focuses entirely on further conceptual arguments.

In fact, after identifying and discussing the shortcomings inherent in the sustainable value approach, we aimed our attention at circumventing the implicit problems of this estimator. By building an explicit link between the sustainable value and frontier approach to environmental performance assessment (e.g., Tyteca, 1996, 1997; Kortelainen, 2008; Färe et al. 1989, 1996, 2012), we proposed a generalized formulation of the sustainable value that assumes a more general definition for the benchmark technology, which can be estimated from empirical data with available frontier methods. We first examined alternative parametric and nonparametric methods for estimating benchmark technology in the context of sustainable value assessment and presented their advantages and disadvantages. Then, we applied the reviewed methods to an empirical data of Finnish dairy farms. It is worth mentioning that in addition to the established methods of productivity analysis, we also applied the recently developed method called Stochastic Nonparametric Envelopment of Data (StoNED) (Kuosmanen, 2006; Kuosmanen and Kortelainen, 2012). This work turned into the second article of this thesis.

Afterwards, our target was to extend the sustainable value methodology from micro (farm level) to macro levels, such as a sector, region or industry levels. While our previous work in Articles I and II was mainly motivated with the current state of a number of sustainability indices and their failure to separate theoretical object of interest and the conceptual rule, consistent aggregation of generalized sustainable values was our work package in the scope of the SVAPPAS project. Thus, the third article of this thesis was designed to come up with a systematic approach to measuring sustainability performance of firms at aggregate level. The proposed method allows estimation of an aggregate sustainability measure from empirical data by applying frontier approaches. To this point, Article III completes the discussion of the sustainable value approach in this thesis.

2.2 Nutrient balance

In agriculture, the nutrient balance (or gross nutrient balance) is a standard approach to estimate surplus or deficit of nitrogen and phosphorus (OECD, 2007a, b). Developed by the OECD and Eurostat (OECD, 2001) it is used as a proxy for the potential level of environmental pressures from nutrients on natural assets, such as soil, water, and air (OECD, 2011b). The nutrient balance is used in a number of studies: in cross–country comparisons (OECD, 2008), from macro to micro levels (Lord et al., 2002; Maticic, 1999; Salo et al., 2007), and in productivity studies (Reinhard et al., 1999, 2000; Coelli et al., 2007; Lauwers, 2009; Meensela et al., 2010; Hoang and Coelli, 2011), among others. Drawing on the notion of nutrient cycle, this approach to modeling nutrients in agriculture relies on the static model of material balance (e.g., Ayres and Kneese, 1969). In practice, the nutrient balance is calculated as the difference between the total quantity of nutrient inputs entering an agricultural system and the quantity of nutrient outputs leaving the system annually. The major nutrient inputs included in the calculations are fertilizers, livestock manure, atmospheric deposition, and other inputs, such as seeds and planting material. The major nutrient output is part of nutrients removed with the harvested crop. Thus, the nutrient balance establishes a link between agricultural nutrient use and changes in environmental quality from nutrient excess (Parris, 1998).

Three main varieties exist to the nutrient balance approach (Oenema et al., 2003; Hoang and Alauddin, 2010). The first is the *farm gate balance*, also known as the "black box" approach. It considers the amount of nutrients in all inputs and outputs entering and leaving the farm and it ignores nutrients recycled within the farm. The second approach is the *soil surface approach*, which 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. The third is the *soil system method*, which records all nutrient inputs and outputs, including nutrient gains and losses within and from the soil. Thus, the main difference among these approaches rests on the definition of the boundary of the defined system and nutrient inputs and outputs. All these methods are regulated by the fundamental law of mass conservation and are based on the conventional material balance equation (Ayres and Kneese, 1969).

The nutrient balance has a number of benefits compared to other environmental indicators. One of the main benefits is that the nutrient balance provides a single common unit for measuring potential environmental pressure from nutrients (it is usually expressed in kilograms of nutrient per hectare) that can be relevant to a wide range of policy contexts. Among other benefits, the nutrient balance is considered to be robust and reliable approach, since calculations of nutrient balances are based on established data such as livestock numbers and crop areas collected according to the standards laid out by Eurostat. Further, the calculation procedure of nutrient balances is rather open and transparent despite a large volume of data (OECD, 2007a, b).

However, the nutrient balance approach has also certain weaknesses. For instance, one source of uncertainty in the nutrient balance is the nutrient content in different inputs and outputs. The input and uptake coefficients differ between countries and in different sources of official statistics. These coefficients are obtained from empirical research and their origin is hard to determine. Another weakness of the nutrient balance approach is that it does not provide any estimation on nutrient losses to air, water, and soil. Further, it is important to note that the nutrient balance provides only an annual estimate of total nutrient loading, but it ignores the accumulation of nutrients and overlooks an important dimension of the nutrient cycle: the time. Nutrient balance measures are flow variables that represent an additional amount of nutrients to the soil, but do not consider long term impact on nutrient stocks. This approach can only be applicable to the flow pollutants which affect the environment immediately. However, nutrients such as nitrogen and phosphorus are prime examples of stock pollutants, which accumulate in the soil over time and have delayed effects on the environment that occur over time. Nutrient cycles in the soil are very slow processes, particularly in the case of phosphorus. Therefore, it is important to consider the stocks of nutrients rather than their flows (Perman et al., 2011).

Following this line of thinking, Article IV of this thesis presents an examination of the standard nutrient balance approach and develops a dynamic model of nutrient balance. By building an intuitive link between the capital stock and investment from the perspective of production theory and the stock and flow of a nutrient in agriculture, the dynamic nutrient balance model allows to construct nutrient stocks from the available data of nutrient balances. The developed model was illustrated by two empirical applications. In the first application, stocks and flows were calculated for two main nutrients in agriculture, nitrogen and phosphorus in Finland (Article IV). In the second application, nitrogen stocks and flows were analyzed for a number of European countries (Article V).

3 Summary of the articles

The thesis consists of five distinct articles, all of which contribute to the main objective of the thesis: to develop new approaches to sustainability assessment in agriculture based on frontier estimation and applying insights from production theory. To clarify the connections between the independent papers, Articles I–III take a broader perspective on measuring sustainability performance of firms at micro and macro levels. These articles are united by a common theme of the sustainable value approach. In contrast to the first three articles, Articles IV and V turn from measuring sustainability performance in general to the subject of a specific environmental issue: nutrient pollution in agriculture. The contributions of the articles are mainly methodological, although empirical applications are also presented. We next take a brief look on those articles by presenting the main contribution and results of each paper and underlining the most interesting aspects of this thesis.

Article I: Kuosmanen, T. and Kuosmanen, N. (2009): How not to measure sustainable value (and how one might)? *Ecological Economics* 69, 235–243.

The starting point of this article was to focus on one of the most compelling and promising indicators in the literature to measuring sustainability performance of firms and to examine its performance and underlying assumptions. The motivation for this work was the fact that many sustainability indicators, where the environmental and social dimensions are aggregated by simple averaging, often fail to distinguish its qualitative concept from operational measure. This implies that practitioners apply sustainability indicators to real world data without properly examined statistical properties, which involves a high risk of biased and misleading conclusions.

As discussed earlier, one of the most promising developments to quantify sustainability performance of firms is the sustainable value approach (Figge and Hahn, 2004, 2005). Based on the notion of opportunity costs, the sustainable value claims to measure firms' contributions towards sustainability in monetary terms. The main purpose of Article I was thus to critically examine the sustainable value approach for opportunity cost. By drawing a sharp distinction between the conceptual idea and the operational estimator, we firstly showed that the sustainable value is a restrictive special case of the standard efficiency indices known in the literature of productive efficiency analysis for decades. Secondly, this indicator requires very strong and rather unrealistic assumptions, even though the conceptual idea is simple and attractive. Specifically, the sustainable value assumes linear production technology for the evaluated firms. From a theoretical perspective, linear functional form implies perfect substitutability between all resources and means violation of the principle of strong sustainability, which would require non–substitutability of at least some forms of capital. Furthermore, specific coefficients of the sustainable value estimator are determined by just a single observation, which, from a statistical perspective, cannot provide enough information for meaningful estimation.

Further, we examined performance of the sustainable value estimator in the controlled environment of Monte Carlo simulations, which is a standard method in econometrics and statistics for examining the finite sample performance of estimators (e.g., Hendry, 1984; Gentle, 2003). Based on results, even under ideal conditions with the data generating process designed to be as favorable as possible to the sustainable value estimator, provided evidence from different scenarios showed that this estimator performs very poorly.

In this study, we next reinvestigated the empirical study of 65 European manufacturing firms conducted by the ADVANCE–project (2008), published by Hahn et al. (2007). Using standard statistical methods, we tested empirically the assumptions of the sustainable value estimator, such that all 65 firm, operating in different industries, have access to the same production technology, characterized by the linear production function with a specific coefficients determined by a single observation. Based on the testing results, we concluded that assessing sustainability performance of such a heterogeneous group of firms with a very crude data set using the sustainable value method with its restrictive assumptions is a questionable exercise. In general, to assess sustainability performance at the firm level, it is crucial to have a relatively homogeneous large enough sample of firms, which can be considered to be similar in their characteristics.

To circumvent the implicit problems of the sustainable value estimator, we proposed a definition of generalized sustainable value. The rationale of this definition is analogous to that of the conceptual definition of the sustainable value. However, the generalized sustainable value does not assume any particular functional form for the benchmark technology but allows resources be independent. Defined as a residual between the observed output and the production function, the generalized sustainable value can be estimated with the established frontier estimation techniques in a straightforward manner. Building upon our generalized definition, we showed that both sustainable value and sustainable efficiency can be viewed as special cases of the standard efficiency indices known in the literature of productive efficiency analysis for decades. Thus, we concluded that the novelty of the sustainable value approach lies in its conceptual links to the constant capital rule and the strong sustainability, although the linear functional form imposed by the sustainable value estimator does not respect the principle of strong sustainability.

Article II: Kuosmanen, T. and Kuosmanen, N. (2009): Role of benchmark technology in sustainable value analysis: An application to Finnish dairy farms. *Agricultural and Food Science* 18, 3025–316.

In this article, the purpose was to start from a generalized formulation of the sustainable value that is consistent with the non–linear benchmark technologies and allows estimation of the benchmarks from empirical data and to review alternative methods for estimating those benchmark technologies and sustainable value scores. In addition to reviewing the theoretical properties and practical implementation of alternative methods, we presented a critical examination of their advantages and disadvantages.

In the context of the sustainable value analysis, we characterized the benchmark technology as a production function, which indicates the maximum amount of output that the benchmark technology can produce using the given amounts of input resources. From this perspective, the generalized sustainable value formulation is simply a residual between observed output and the production function, which conforms with the classic approach to measuring performance differences across firms based on regression residuals (see e.g. Timmer, 1971 and Richmond, 1974). Altogether we provided a detailed examination and classification of eight alternative methods available for estimating the benchmark technology. The methods were classified between: 1) parametric and nonparametric approaches based on assumed functional form of the benchmark technology, 2) an average–practice and best–practice approaches, with further classification of the best–practice approaches into deterministic and stochastic methods. One should note, that for each category exist sound estimation methods that can be applied in empirical analysis of sustainability assessment.

To demonstrate the benefit of using alternative methods for estimating benchmark technology in sustainability assessment, we applied reviewed approaches to an empirical data of 332 Finnish dairy farms. Instead of using the sustainable value estimator with its linear benchmark technology identified by just a single data point, we demonstrated how to estimate a more general benchmark technology from empirical data using available methods. This study includes the first empirical application of StoNED method, followed by several recent applications (Kuosmanen, 2012; Mekaroonreung and Johnson, 2012; Eskelinen and Kuosmanen, 2013; Kuosmanen et al, 2013; Dai and Kuosmanen, 2014).

Based on the application, we concluded the following. Due to the greater flexibility of the nonparametric specification, the nonparametric methods achieved a better empirical fit than their parametric counterparts in terms of the coefficient of determination (R^2). Further, significant negative skewness in the regression residuals of both parametric Ordinary Least Squares and nonparametric Concave Nonparametric Least Squares speak against using the average–practice benchmarks in this application. High positive correlations across a wide spectrum of methods (except for Data Envelopment Analysis) in both the sustainable value estimates and the relative rankings suggest that the findings from the regression based approaches are relatively robust to possible specification errors, sampling errors, and data problems. Finally, due to a number of omitted factors and sources of error in the data, the stochastic frontier methods SFA and StoNED, which filter out the noise component from the inefficiency term, are likely to provide more realistic estimates of the sustainable improvement potential.

To conclude, the results of the empirical analysis revealed the critical role of both parametric functional form assumptions and the importance of accounting for stochastic noise. To this end, several methods exist allowing the estimation of the benchmark technology in the context of the sustainable value analysis. The choice of the method would depend on the quality of data, the sample size, the number of considered resources, among other factors. The application showed that applying several alternative methods and reporting their estimates can shed further light on the robustness of results.

Article III: Kuosmanen, N., Kuosmanen, T. and Sipiläinen, T. (2013): Consistent aggregation of generalized sustainable values from the firm level to sectoral, regional or industry levels. *Sustainability* 5, 1568–1576.

While in two previous articles the focus was on the firm level analysis, the aim of this paper was to develop a systematic approach for a consistent aggregation of the firm level sustainable value indices to an aggregate level, such as sectoral, regional, or an industry levels. The main contribution of this paper was to show that general definition of the sustainable value, proposed in Article I is not restricted to the firm level analysis, but consistent aggregation is also possible. In Article III, consistent aggregation implies that the sustainable value scores of individual firms can be added up to obtain a sustainable value score of the aggregate entity, and that the same result would be obtained if one assesses the sustainable value of the aggregate entity directly.

To develop a simple but systematic aggregation scheme, we first introduce a representative firm, which is characterized by the average output and average resource vectors of a group, to the data sample as an additional entity to this group. After estimating the common benchmark technology by some econometric method, the aggregate generalized sustainable value of this group is calculated as the generalized sustainable value of the representative firm multiplied by a number of entities in the group.

Aggregation of the sustainable values was illustrated by an empirical application to Finnish crop and dairy sectors. The benchmark technologies were estimated by data envelopment analysis (DEA) mathematical programming technique. The estimated efficiencies of the representative farms allow one to assess the performance of an average farm in each sector in terms of resources used and to compare the performance of average farms between the sectors. For instance, based on the results given by DEA, the representative crop farm achieved only about half of its potential output, while efficiency of the representative dairy farm was slightly higher. Further, the aggregate generalized sustainable value method can be usefully applied in a comparative analysis of different sectors.

Article IV: Kuosmanen, N. and Kuosmanen, T. (2013): Modeling cumulative effects of nutrient surpluses in agriculture: A dynamic approach to material balance accounting. *Ecological Economics* 90, 159–167.

The aim of this article was to address both the theoretical and practical problems of the nutrient balance method, which is used by the OECD and Eurostat to estimate the environmental pressures from nutrients use in agriculture at the aggregate level of countries. Firstly, drawing on the notion of nutrient cycle, the nutrient balance approach is based on the conventional material balance equation, which ignores time. Strictly, this means that the nutrient balance method can be applied only to the flow pollutants which affect the environment immediately. However, nutrients such as nitrogen and phosphorus are primary examples of stock pollutants: they accumulate to the soil and cause a delayed impact on natural assets occurring over time. Secondly, the nutrient balance estimates are widely used for developing indicators of environmental performance in agriculture, both at farm level and at the aggregate levels of regions and countries. It is worth noting that nutrient balance estimates can take negative values for some countries in some periods, and even more frequently at farm level. Technically, as the nutrient surplus is defined as the difference between the inputs and outputs of nutrients, nutrient balance estimates are interval scale variables. This means that mathematical operations such as multiplication or division are invalid. 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.

Therefore our primary goal in this paper was to develop an approach that would allow to analyze the impact of an excessive use of nutrients over time and able to consider nutrients as stocks rather than flows. Building upon the standard model of capital accumulation used in production economics, we proposed a dynamic model of nutrient balance by making 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 inflow of a nutrient to the stock. The proposed model takes time and accumulation of nutrients explicitly into account. Furthermore, it allows breaking down the total nutrient outflow into several components (e.g., nutrients lost to water, air, and soil) using the elements of total decay rate (e.g., leaching rate, denitrification and volatilization rates).

The proposed dynamic model was then applied 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 showed 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 dynamic modeling of nutrient stocks can provide more interesting and relevant information beyond the conventional material balance accounts. For example, we found the decay of nutrients (or nutrient outflows from the stock) to be considerably more stable over time compared to the nutrient inflows, which is a desirable property for an indicator of agri–environmental performance. Importantly, both the nutrient stock and the decay (outflow from the stock) are non–negative variables by construction.

In the case of nitrogen, we found that the nutrient balance approach may overestimate the environmental pressure in periods where the nitrogen stock is increasing, and underestimate when the nitrogen stock is decreasing. This is because the nitrogen stock adjusts to the changes in the nitrogen inflow with considerable delay. In the case of phosphorus, the use of static nutrient balance model provides a different picture on the pollution problem than the dynamic nutrient balance model. Based on the phosphorus inflow estimates calculated with the nutrient balance equation, the analysis would suggest that the phosphorus emissions increased dramatically in the 1960s, followed by a radical decrease of phosphorus emissions since the late 1980s. However, the estimates of the dynamic model suggest that the quantities of phosphorus outflow have not fluctuated as much as the static model tells. This is due to the fact that phosphorus has a very slow biochemical cycle, and hence the phosphorus stock and thus outflow from the stock respond to the changes in the inflow of phosphorus with a considerable delay.

Article V: Kuosmanen, N. (2013). Estimating stocks and flows of nitrogen: Application of dynamic nutrient balance to European agriculture. Submitted for review.

The aim of Article V was to further elaborate the dynamic material balance approach introduced in Article IV and to apply it to European agriculture. We distinguished at least four benefits of the dynamic modeling compared to the conventional nutrient balance approach. First, the dynamic model allows estimation of total outflow of nutrient from the stock (or stock decay), which is conceptually more relevant and interesting proxy for potential environmental pressures from nutrients on natural assets than nutrient inflow. Second, the empirical evidence showed that nutrient outflows are much less volatile over time compared to the nutrient inflows, which is a better property for an indicator to not over or underestimate the pollution levels. Third, using the dynamic material balance one can estimate different pathways of nutrients from the stock to the environment, such as to water, air, and soil. Fourth, while the nutrient balance is defined on the interval scale, the estimates of the dynamic modeling are ratio scale variables. This means these estimates can be used as environmental indicators to assess environmental performance in agriculture and be used for calculating other measures, e.g., nutrient efficiencies.

We next applied the dynamic nutrient balance model to estimate inflows, stocks and outflows of nitrogen in 14 European countries covering the years 1961–2009. The primary purpose of this application was to illustrate the benefits of the dynamic modeling. First, we compare nitrogen inflows, which are currently in use as proxies for the nitrogen pollution, with the nitrogen outflows provided by the dynamic model. Second, we use stock estimates to calculate nitrogen efficiencies and rank the countries in terms of their nitrogen use in producing agricultural output. The results are presented in comparison with other partial productivity measures. We also present a sensitivity analysis that aims to assess the robustness of the dynamic nutrient balance model.

The results of the empirical application revealed that the decay rate of 34 percent seems a reasonable approximation for all countries despite different soil conditions and production structure. Country specific decay rates obtained in the sensitivity analysis of the dynamic material balance ranged between 33 to 35 percent. Further, the calculated nitrogen inflows and outflows resulted in almost perfect balance in all countries. The annual variation in the nitrogen inflows are much larger in all countries compared to the variation in the nitrogen outflow. The results of the sensitivity analysis revealed that the misspecification of the decay rate and having different initial stock levels does not have considerable effect on the relative ranking of countries.

4 Concluding remarks

The main objective of this study was to contribute to the approaches of sustainability measurement literature and to develop new methods based on the insights from the production theory and frontier estimation. The first three articles elaborated the sustainable value approach as frequently used to assess firms' contributions towards sustainability. In contrast to many other sustainability indicators and measures, the proposed generalized sustainable value method allows assessment of firms' performances taking into account different dimensions of sustainability by using econometric techniques with proven statistical foundation. We believe that the proposed measure of the generalized sustainable value, build on the existing performance measurement tools from productivity and efficiency literature combined with the conceptual idea of the conventional sustainable value method, can be particularly useful in different agricultural applications both at farm and more aggregate, e.g., regional or sectoral levels.

The last two articles of this thesis reinvestigated the conventional nutrient balance approach frequently applied to modeling nutrient pollutions from agriculture. Built on the link between capital stock and investment in production theory and nutrient stock and flow in agriculture, the dynamic model of nutrient balance provides both interesting insights in modeling cumulative effects of nutrients in agriculture and also various application possibilities for the assessing nutrient emissions. For instance, it would be interesting next to extend the dynamic material balance to the disaggregate levels of individual farms and include it with the total factor productivity analysis. Similar to the cross–country application of nitrogen, it would be interesting to analyze stocks and outflows of phosphorus emissions. Another promising application area is productivity and efficiency analysis, where the estimates of the stock and the outflows can be used as either input (stock) or undesirable outputs (flows from stock to air, soil, or water).

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