Evaluating farmers' provisioning of soil ecosystem services to inform agri-environmental policy

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Abstract
Conserving soil natural capital contributes to human welfare through its delivery of ecosystem services such as food security, water quality and climate regulation as well as providing insurance against future uncertainties, particularly climate change. However, individual farmers bear conservation costs, whereas particular services are public goods benefiting humanity generally. Consequently, farmers' self-interested behaviour will not necessarily promote the optimal management of soil ecosystem services and underlying natural capital. Here we present a roadmap for evaluating the impacts of alternative farming practices that conserve soil ecosystem services, on farmers' and societal welfare. The results of a Swedish case show that the value of conserving soil natural capital diverges depending on the level of decision-making: farmers or society. This is because public-good services have substantial societal value, and future flows of provisioning services have greater value to society than to current-generation farmers. We conclude that market outcomes are not likely to be generating optimal conservation of soil natural capital from society's perspective. Innovative information systems and governance institutions are needed to guarantee the welfare of future generations.

Keywords: (3-10) natural capital; soil carbon; policy; valuation; climate change; food security; nutrient retention

1 Introduction

Well-functioning agricultural soils generate in addition to provisioning ecosystem services such as food, fibre and biofuels, a range of regulating and supporting ecosystem services that are crucial for agriculture (Barrios, 2007). These include climate and water regulation, pest and disease control, nutrient cycling, pollination, and control of crop pests and diseases; and cultural services such as biodiversity, aesthetic or spiritual values, recreation and knowledge (Adhikari and Hartemink, 2016).

Intensification of agricultural production over recent decades has, however, had profound negative effects on both the levels of ecosystem services generated by soils and their resilience (Cassman, et al., 2003). This is undermining agricultural productivity (Bommarco, et al., 2013), accelerating climate change (Lal, 2010) and contributing to water pollution (Shortle and Horan, 2017). One reason for this is that farmers' production decisions tend to be based on short-term analyses that ignore the long-term effects of management on levels of ecosystem services. Another reason is that farmers are not likely to be considering the value of public-good services in their production decisions, because providing public goods can be costly to them while the benefits are enjoyed by society generally (Lal, 2014). For these reasons there is a need for decision analysis of different agricultural management practices that consider the long-term effects of management choices and at multiple levels; from individual farmers to policymakers acting in the interests of society.

Quantifying changes in ecosystem services and valuing these changes can be used to inform decision makers of the benefits of allocating resources to conservation of soil ecosystem services, and the design of policy instruments that might be necessary to ensure the generation of ecosystem services in socially desirable quantities. In this article we develop a roadmap for valuing the impacts of alternative agricultural management practices on soil ecosystem services to inform multi-level decision-making.

We value changes in flows of different types of ecosystem services and infer from this changes in underlying stocks of soil natural capital, and demonstrate the approach through an application to a study region in Sweden. Since ecosystem services have value to farmers and to society in different ways, decisions have to be taken at appropriate levels in order to manage ecosystem services efficiently. We therefore value soil ecosystem services affected by agriculture to inform decisions taken at the following three scales (levels):

Local (Farm): Decisions concerning farmers' potential to improve flows of supporting ecosystem services to reduce the long-term need for fertilizers, pesticides and fossil energy to sustain yields, and thereby promote ecologically and economically sustainable framing.

Regional (e.g., County Board): Decisions encompassing initiatives to implement regional policy schemes that are adapted to local soil conditions, climatic factors, and crop management practices to minimize the negative environmental impacts of agriculture. It also includes decisions about how to get farmers to incorporate the value of ecosystem services into "good farming practices".

National: (e.g., EPA): Decisions related to optimizing the societal benefits of soils, particularly the need for development of strategies and economic incentives for sustaining public-good ecosystem services related to land management.

To illustrate our road map for valuing soil ecosystem services to inform multi-level decision-making, we apply the approach to an arable cropping region in Sweden. We limit the evaluation to three public-good ecosystem services that are affected by agriculture in the region, carbon sequestration that mitigates climate change, nutrient retention that improves water quality in the Baltic Sea and agricultural productivity that affects future food security. The specific measure we evaluate is the inclusion of different proportions of a multi-year grass cover in the standard arable crop rotation in the region, which comprises either some or all of the following crops: winter wheat, winter oilseed, spring barley and sugar beet.

2 Materials and Methods

1.1 Case-study region

The study region is known as Götalands södra slättbygder or GSS and is one of Sweden's eight naturally defined agricultural production regions. Agricultural production conditions within the region are relatively homogeneous and agricultural land-use dominates the landscape. Accordingly, fields are generally large, open and well connected with farm centres. It is characterised by specialized arable farming using intensive production technologies. The standard yields and nitrogen fertilizer input rates are respectively for the four main crops: winter wheat 7.9 t/ha and 160 kg N/ha, b) spring barley 5.7 t/ha and 91 kg N/ha, c) winter oilseed 3.6 kg/ha and 172 kg N/ha, and d) sugar beet 60 000 kg/ha and 120 kg N/ha (SCB, 2013).

Due to the long history of intensive arable cropping and lack of organic matter inputs to the soil such as application of stable manure, soil organic carbon (SOC) content is relatively low compared to bordering regions where livestock production and perennial grass crops dominate. Average SOC content in arable fields across GSS is 1.7 %SOC based on measurements covering 33% of the arable area in the region (HS, 2017). Some 50 years ago the soils in GSS had SOC content in the range 2.7-4.4 %SOC (Brady, et al., 2015), which implies that intensive arable cropping practices have resulted in declining SOC content. It is therefore estimated that SOC content declines at an annual rate of 0.5% relative to the preceding year if additional conservation measures are not taken. Our underlying assumption in the coming simulations is that all farms in the region are managed using conventional practices and no particular measures are taken to maintain soil carbon, other than incorporation of harvest residues in the soil through ploughing. A relative increase of 1% p.a. is assumed to be possible if a multi-year grass fallow is included in the normal rotation of annual cash crops (Alvarez, 2005, Blair, et al., 2006, Luo, et al., 2010, Thomsen and Christensen, 2004).

1.2 Farm-level

1.2.1 Estimation of agri-ecological production functions

To quantify the impacts of changes in flows of supporting ecosystem services on agricultural productivity to inform farm-level decision making we estimated the following quadratic production function for each of the main crops in the study region (Brady, et al., 2015):

$$Y(C,N) = a_1 + a_2 N + a_3 N^2 + a_4 C + a_5 C^2 + a_6 NC \qquad (1)$$

where Y is yield (kg ha^{-1}), N is total input of mineral and plant-available nitrogen in manure (kg N ha^{-1}), and C is SOC content in the topsoil in percent. To qualify as a production function for agriculture the following conditions must apply: $a_2, a_4 > 0$; $a_3, a_5 < 0$; whereas a_1, a_6 can be either positive or negative (as long as $4a_3 a_5 \geq a_6^2$). These conditions simply imply that the function conforms with common knowledge of agricultural production; that yield is increasing in *N* and *C* but at a diminishing rate, and that *N* and *C* can be either complements or substitutes. An important difference between the variables is that farmers choose N directly, whereas C is determined indirectly through their historical choices of soil management practices. Accordingly, farmers cannot influence *C* in the short-run while N can be applied according to needs.

1.2.2 Farmers' profit maximization problem

Once the agri-ecological production functions have been estimated they can be used to determine the implications of changes in supporting ecosystem services on agricultural productivity, i.e., maximum yield and optimal fertilizer input rates, and thereafter farmers' profits.

A farmer's short-term decision problem is about maximizing their profit given the current level of supporting ecosystem services, which we denote $\bar{C}$. If we replace the variable *C* in Eq. (1) with $\bar{C}$ and let *p* be the product price and *w* the unit cost of applying fertilizer *N*, while other costs are assumed to be constant, then the farmer's short-term profit maximization problem for a particular unit of land can be formulated as:

$$\pi_{\max}\left(N \mid \bar{C}\right) = \max_{N} pY\left(N \mid \bar{C}\right) - wN. \tag{2}$$

Since the production function is assumed to be concave then the profit function will also be concave and the maximum short-term profit defined by the first-order condition:

$$\frac{\partial \pi}{\partial N} = p\left(a_2 + 2a_3N + a_6\bar{C}\right) - w = 0. \tag{3}$$

From condition (3) it follows that the optimal input of fertilizer, N^*, given SOC content $\bar{C}$ is:

$$N^* = \frac{w - p\left(a_2 + a_6\bar{C}\right)}{2a_3 p}, \tag{4}$$

which implies that an increase (decrease) in *C* will result in a reduction (increase) in the optimal fertilizer N input if $a_6 < 0$ (Brady, et al., 2015).

Finally the optimal yield is found by inserting $\bar{C}$ and N^* in the production function, Eq. (1), giving:

$$Y^* = a_1 + a_2N^* + a_3\left(N^*\right)^2 + a_4\bar{C} + a_5\bar{C}^2 + a_6N^*\bar{C}. \tag{5}$$

This implies that *N* and *C* can substitute for each other to a certain degree, but not completely, hence lower *C* will give a lower profit and vice versa given that $a_6 < 0$.

These equations will be used to evaluate the impacts of changes in supporting services brought about by alternative soil management practices on yields, optimal fertilizer input and farm profits.

1.2.3 Marginal value of supporting soil ecosystem services

To determine the impact of a marginal change in flows of supporting soil ecosystem services on the farmer's maximum profit, one simply differentiates the optimized value of Eq. (2), known as the value function and denoted here π^*, with regard to $\bar{C}$ (by the Envelope theorem). After plugging in N^* this implies $\pi^* = pY\left(N^* \mid \bar{C}\right) - wN^*$, and

$$\Delta\pi^* = \frac{\delta\pi^*}{\delta\bar{C}} = p\left(a_4 + 2a_5\bar{C} + a_6N^*\right). \tag{6}$$

Given that supporting ecosystem system services are generated by an underlying stock of soil natural capital, it follows that the implied change in the value of the farmer's stock of natural capital is the present value of the change in the stream of maximum future profits $\Delta\pi^*$ defined by Eq. (6), which for an infinite future is:

$$PV = \Delta\pi^* \sum_{i=0}^{\infty} \frac{1}{(1+\delta)^i} = \frac{\Delta\pi^*(1+\delta)}{\delta}, \quad (7)$$

where δ is the discount rate and *i* the period. The annuity defined by Eq. (7) is defined over an infinite time horizon because land that is managed sustainably has an infinite lifetime. Since discounting reduces the current value of future profits, those profits arriving in the distant future will asymptotically decline to zero.

1.3 Regional level

To simulate impacts on agricultural production and public-good ecosystem services of the alternative soil management scenarios, we applied the agent-based AgriPoliS model of regional agricultural structures (Balmann, 1997, Happe, et al., 2006); and through its capacity to model multiple ecosystem services (Brady, et al., 2012) adapted it for the purposes of this study using the indicators of public-good services described below (Hristov, et al., 2017). In this way we developed public-good production functions based on simulation.

1.3.1 Climate mitigation through carbon storage and reduced GHG emissions

The public-good service climate regulation as modelled here has two components. First, changes in SOC content imply that concentrations of carbon dioxide in the atmosphere, and hence global warming potential, will change proportionally with the amount of carbon stored in the soil. The amount of carbon stored in the soil as a function of SOC content (%SOC) is approximated as:

$$C\_store = SOC \times (1 - STONES) \times soil\_bulk\_density \times soil\_volume \quad (8)$$

where *SOC* and *STONES* are the proportions of *C (i.e., %SOC/100),* and stones and gravel in the topsoil respectively, *soil_bulk_density* is the weight of a particular volume of the top soil (kg dm^{-3}) and *soil_volume* is the volume of soil in one ha of land measured to a particular depth (dm^{-3}). The current C stock in the region is, according to Eq. (8) and the assumed parameter values:

$$C\_store = 0.0171 \times (1- 0.08) \times 1.59 \times (3 \times 10^6) = 75\,042 \text{ kg ha}^{-1} \text{ or } 75.0 \text{ t ha}^{-1},$$

which is comparable to the average C stock calculated across the five LTE sites of 81.4 t ha^{-1}.

Second, the production of mineral N fertilizers causes substantial emissions of GHG, hence any change in farmers' demand for N fertilizers due to changes in supporting ecosystem services, will also have implications for the climate. In this study, we restrict our evaluation to emissions generated during fertilizer production, thereby ignoring potential emissions from application (which can be substantial but very uncertain). The production of 1 kg N for the Swedish market is assumed to result in the emission of 3.39 kg CO2e (Höjgård and Wilhelmsson, 2012).

1.3.2 Water quality improvement through nutrient retention

As a change in supporting ecosystem services affects agricultural productivity it will indirectly affect water quality through nutrient retention. In particular, the choice of crop and fertilizer input rate influence the rate of leaching from arable land. For instance a multi-year grass crop has a substantially higher nitrogen retention capacity than annual crops (Table 1).

A change in the rate of N fertilizer application has the potential to impact N emissions to the Baltic Sea due to its influence on nutrient leaching from arable fields (Wulff, et al., 2014). An increase in the fertilizer input rate is likely to increase leaching and vice versa. To link AgriPoliS results for a particular crop *i*, unit of land *j* and period *t* to N emissions to the Baltic Sea, $e_{i,j,t}$, we apply the following model developed by Simmelsgaard and Djurhuus (1998) for southern Scandinavian conditions:

$$e_{i,j,t}\left(N_{i,j,t} \mid \bar{N}_{i,j,0}, \bar{C}_{j,t}\right) = \bar{e}_{i,j} * \exp\left[\beta_j \left(\frac{N_{i,j,t} - \bar{N}_{i,j,0}}{\bar{N}_{i,j,0}}\right)\right] * R \tag{9}$$

where $\bar{N}_{i,j,0}$ is the current optimal (or normal) rate of N input to crop *i* on field *j* given current SOC content in the field, $\bar{C}_{j,0}$; $N_{i,j,t}$ is a new optimal N input to crop *i* on field *j* given a new SOC content $\bar{C}_{j,t}$ in period *t* per Eq. (4); $\bar{e}_{i,j}$ is the normal amount of leached N from crop *i* on field *j* given normal N input; β_j is the leaching potential of soil type *j*; and *R* the average proportion of leached N that actually reaches the Baltic Sea from arable fields in the region due to retention processes in waterways. The function was parameterized with crop-specific data for the study region according to Table 1 and the associated references.

Table 1. Crop-specific parameters for nitrogen emissions to the Baltic Sea

Crop	$\bar{e}^1$	β^2	R^3
Winter wheat	37	0.71	0.75
Spring barley	42	0.71	0.75
Winter oilseed	54	0.71	0.75
Sugar beet	26	0.71	0.75
Multi-year grass fallow	17	n/a	0.75

Sources: The study region corresponds to the Swedish leaching region (läckageregion) 1a of 22 such regions and associated parameter values: 1) normal crop leaching rate from arable land (Blombäck, et al., 2011, Tabell 4:1 for a sandy-loam soil), 2) soil-related leaching potential (Simmelsgaard, 1998), and 3) retention in water ways during transport to the Baltic Sea is assumed to be 25%, but could be as low as 10%, implying a conservative assumption about this factor (Brunell, et al., 2016, p. 34).

1.3.3 Future food security through conservation of soil productivity

Conservation of soil natural capital contributes to food security because it is a necessary input to agriculture (Sunderland, 2011). This implies that any changes in the productivity of agriculture related to changes in soil natural capital needs to be considered in an evaluation of societal welfare, because it reflects a change in the capacity of the soil to feed future generations (Brunstad, et al., 2005). In order to value changes in the underlying stock of natural capital we assume that the stock's value, as with financial assets such as shares and bonds, depends on expected future profits. Following from Eq. (2), we denote $\pi_t^*\left(N_t^* \mid \bar{C}_t\right)$ as the expected average profit in the region in period *t* given supporting ecosystem services $\bar{C}_t$ and optimal fertilizer input N_t^*. Assuming that land has an infinite lifetime the implied change in the average value of the stock of soil natural capital per ha in year *T* is therefore:

$$\begin{aligned} \Delta NC_T &= \frac{\pi^*\left(N_T^* \mid \bar{C}_T\right)}{\delta} - \frac{\pi^*\left(N_0^* \mid \bar{C}_0\right)}{\delta} \\ &= \frac{\pi_T^* - \pi_0^*}{\delta} \end{aligned} \tag{10}$$

where t=0 is the current period and t=T denotes some finite period in the future, and as previously δ is the social discount rate. In words, Eq. (10) calculates the difference between two annuities in period T; that based on current maximum profit per ha and maximum profit at the end of the evaluation period (which in our study is $T=20$). Note that in the ensuing benefit-cost analysis ΔNC_T must be converted to its current value which we show below.

To determine the total change in the value of soil natural capital in the region in period T one need only multiply ΔNC_T by the area of agricultural land (given that ΔNC_T represents the average change in value per ha). In our simulations with AgriPoliS π^* is optimized for each individual field and farm in the model landscape, and thereafter the change in the value of the stock of natural capital is calculated based on the average profit per ha according to Eq. (10).

1.4 National level

To evaluate the effects of the alternative management scenarios on societal welfare we first derive marginal values of the public-good ecosystem services and thereafter the formula for aggregating multiple welfare impacts to the societal or national level. These valuations are based, as far as possible, on Swedish citizens' preferences, to be consistent with principles of welfare economic analysis at the national level (OECD, 2001).

1.4.1 Marginal values of public-good ecosystem services

In order to compare potential changes in private and public-good ecosystem services we derived marginal values of the public-good services using results of relevant nonmarket valuation studies. Further, we assume that the potential changes in private and public-good services would not be sufficient to influence market prices (Sweden is a small country) or the derived marginal valuations of public-good services. In this respect, we illustrate the principles of economic valuation for informing policymaking, but do not answer the question as to what the optimal area of a particular management scenario would be.

The Swedish parliament has responded to the threats posed by climate change by legislating a carbon tax on petrol at 113 €/t CO2e (Government Offices of Sweden, 2019)[1]. Since this tax rate has emerged from the Swedish parliament as a product of political deliberation, it can be argued that it reflects citizens' preferences (De Nocker, et al., 2004). Although relatively high it is in the vicinity off the range of rates that have previously been estimated for a globally optimal carbon tax of 46 to 230 €/t CO2e (Crost and Traeger, 2014, Warren, 2014)[2]. Consequently, we adopt the tax rate set by the Swedish parliament as our High marginal value to Swedish citizens of climate regulation services, i.e., 113 €/t CO2e. However, since this valuation is uncertain we also test a Low valuation based on the price of CO2e emissions permits under the EU's emissions trading system, EU-ETS, of 6 €/t CO2e (Carbon Pulse, 2016). It should though be kept in mind that the high valuation is more likely to reflect Swedish citizens' preferences because it is based on Swedish policy.

A major environmental problem related to nutrient emissions from agricultural land to water in the region is eutrophication of the Baltic Sea (HELCOM, 2018). Retention of nutrients by Swedish soils provides therefore an ecosystem service in the form of better water quality. Ahlvik and Ahtiainen (2014, Table A3) have derived marginal values of changes in Baltic Sea water quality under alternative assumptions about water quality i) the current, poor quality of

[1] The Swedish tax rate of 1180 SEK/t CO2e was converted to Euro using the exchange rate 10.40 SEK/€. Source: Sveriges riksbank. *Search interest & exchange rates* as at 20190204 from https://www.riksbank.se/en-gb/statistics/search-interest--exchange-rates/.

[2] The cited rates of US$40 to US$200/t CO2e were converted to Euro using the exchange rate 0.87 $/€ as at 20190204 from https://www.x-rates.com/historical/?from=USD&amount=1&date=2019-03-21

the Baltic Sea and ii) assuming that the water quality goal for the Baltic Sea Action Plan (BSAP) is achieved. Since our study area is in southern Sweden we adopt their estimate of 11 460 €/t N for the Baltic Sea Proper Basin from its current poor state, as our High valuation of the marginal benefits to Swedish citizens of improving water quality. To test the sensitivity of the results to this valuation we also test a low valuation of 270 €/t N based on Swedish citizens willingness-to-pay assuming that good water quality has been achieved.

1.4.2 Calculating changes in societal welfare

To evaluate the net impact of different soil management practices on societal welfare (ΔSW) we apply the principles of benefit-cost analysis (BCA), whereby a net present value is calculated over the evaluation period that considers both the impacts on farmers and public-good services:

$$\Delta \mathrm{SW} = \sum_{j=1}^{J} \mathrm{PV}_j + \sum_{t=0}^{T} \frac{\mathrm{SEQ}_t + \mathrm{RET}_t + \mathrm{FERT}_t}{(1+\delta)^t} + \frac{\Delta NC_T}{(1+\delta)^T} \tag{11}$$

where PV_j is the economic impact on farmer *j* in the population of *J* farmers over the evaluation period *T* according to Eq. (7); and SEQ_t the change in the value of carbon sequestration services, RET_t in nutrient retention services, FERT_t in GHG emissions from the production of mineral fertilizer in period t; and the last term containing ΔNC is the present value of the change in soil natural capital (future food security) according to Eq. (10). Importantly Eq. (11) takes into account peoples' time preferences through the discount rate δ, bearing in mind that benefits occurring in the future are less valuable than a benefit occurring today (Arrow, et al., 2013). We apply a standard social rate of discount used in Sweden of 3.5% in the evaluation (Svensson and Hultkrantz, 2014).

Note that we calculate the change in the value of soil natural capital from society's perspective only (by applying a social rate of discount). Based on the premises of this study we assume that farmers are not aware of potential changes in their soil capital due to the adoption of the alternative management scenarios, because they currently lack information about the impacts of changes in supporting ecosystem services on their profits. Otherwise one could decompose ΔNC into a portion affecting farmers' wealth by applying a private rate of discount, and another portion reflecting any additional value attributable to society having a lower rate of discount than farmers.

3 Results

Three alternative management scenarios were tested where three different proportions of grass production in the crop rotation of specialized arable farms were applied: 5%, 15% and 25% of the area sown to annual crops. The highest proportion of grass in the rotation is approximately that required in organic agriculture to provide green manure in the absence of livestock manure to meet crop nutrient needs. The grass production is a part of the crop rotation and can remain for several years in the same field but is not a permanent grassland.

1.5 Farm level

The effects of changes in flows of supporting ecosystem services on agricultural productivity were quantified with the quadratic production functions, Eq. (1), describing the relationship between yield, supporting ecosystem services (changes in SOC content) and N-fertilizer input rates (see Table S2 for the region's four main crops). The production function for winter wheat (Figure 2a) shows the possible yields given current SOC content (Table S1) for increasing N fertilizer rates; and those for scenarios with a **Higher** and **Lower** SOC content assuming that

SOC content increases or decreases at an annual rate of 1% relative to the previous year's content (which over 20 years in the case of an increasing rate would result in a 22% relative increase compared to the current stock, e.g., from 1.71 to 2.09 %SOC and in the case of a declining rate from 1.71 to 1.40 %SOC). Yield increases in response to higher SOC content and/or fertilizer input rates, but the effects are diminishing with additional increments in SOC or fertilizer giving progressively smaller increments in yield (Eq. (4)). As a result, the marginal revenue earned by farmers for increasing fertilizer input is declining (Figure 1b). The optimal N-rate given a particular SOC content, as defined in Eq. (4), occurs when the marginal revenue of applying an additional kg of fertilizer is equal to its cost (i.e., where the relevant marginal revenue curve intersects the line Price_N in Figure 1b, which denotes the constant marginal cost of applying fertilizer). The optimal yield increases and associated N rate decreases with higher SOC content, because of the implied increase in supporting ecosystem services. Consequently, higher flows of supporting services implies a higher gross margin for farmers all other things equal, because they can produce higher yields with lower inputs of costly mineral fertilizers.

Note that the economic optimal yield is not the maximum yield, but that generating the maximum profit. This is because achieving the maximum yield generates higher costs then revenues on the margin, and hence from an economic perspective would be inefficient.

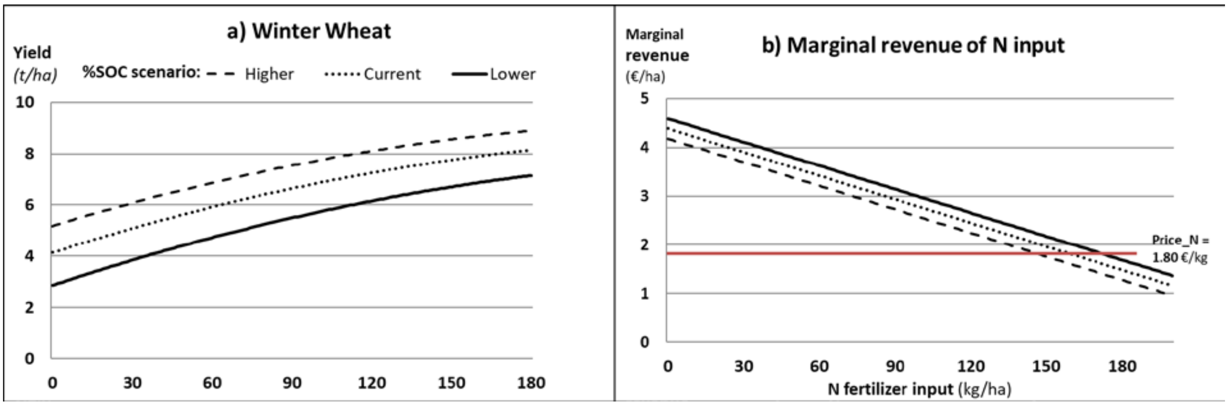

Figure 1. The winter wheat a) production function for different SOC content scenarios: Current, Higher and Lower content; and b) associated marginal revenue functions calibrated to the standard yield (7.9 t/ha) and optimal fertilizer rate (160 kg N/ha) for the current average SOC content in the study region (where Current content is 1.71 %C).

After integrating the estimated production functions for each crop with the farmers' parameterized profit function, Eq. (2), using the price and cost data detailed in Table S5, the impacts of a marginal change in flows of supporting services on standard yield, fertilizer rate, and gross-margin for each crop and the average farm in the study region were derived (Table 2).

Our simulations with the farm-level model predict that an annual 1%, relative increase in the stock of soil natural capital over a period of 25 years would result in a 28% increase in the soil capital stock and a corresponding 18% increase in the average farm's gross margin. Conversely, a 1% annual decline in the stock would reduce its value by 22% after 25 years and annual farm gross margin by 20%. Clearly, the long-term impacts of (dis)investing in soil natural capital are substantial compared to the short-term impacts, which are small. So small in fact that they are unlikely to be detectable by the famer from one year to another, because these changes are smaller than the normal variation between years due to the weather.

The results show that a reduction in soil natural capital can be partially compensated by increasing fertilizer rates, but not fully, since maximum yield is always lower for lower stocks of soil natural capital (Figure 2). As a result, a decline in natural capital will have a relatively larger impact on profit than yields, because fertilizer is costly. If farmers do not have tools to quantify the long-term impacts of their soil management choices on their natural capital, it is therefore likely that its value will be underestimated in their production decisions.

Table 2. Impacts in the following year of a 1% relative reduction in SOC content from the current level (%SOC = 1.71) for the average farm in the study region.

	Yield	**Fertilizer**	**GM**	**ΔYield**	**ΔFert**	**ΔGM**
Crop	*(kg/ha)*	*(kg/ha)*	*(€/ha)*	*(kg/ha)*	*(kg/ha)*	*(€/ha)*
Winter Wheat	7 900	160	752	-33.74	0.58	-5.50
Spring Barley	5 700	91	421	-10.87	0.29	-1.64
Winter Oilseed	3 600	172	707	-47.91	0	-14.00
Sugar beet	60 000	120	2 538	-318.43	1.96	-13.47
Ave. Farm	n/a	**141**	**841**	n/a	**0.56**	**-6.60**

To quantify the long-term impact of changes in soil natural capital on farmers' welfare one needs to value the change in the value of their stock of soil natural capital. Now that we have quantified the impacts of changes in supporting ecosystem services on yields, optimal fertilizer input and gross margins, we can value the implied change in the value of their soil natural capital by plugging the annual change in average farm gross margin of 6.60 €/ha (Table 2) into Eq. (7) for various rates of discount (Figure 3). For instance if farmers degrade flows of supporting services by 1% compared to the current level as indicated by SOC content, then the implicit value of their soil natural capital will, on average, decline by around 200 €/ha if they discount the future at 3.5%. This implies that it would be worth the farmers while to invest up to 200 €/ha to avoid a 1% loss of soil capital. Similarly, if they pay less regard to the future, as indicated by a 7% discount rate, then they would be motivated in investing only 100 €/ha to conserve soil natural capital.

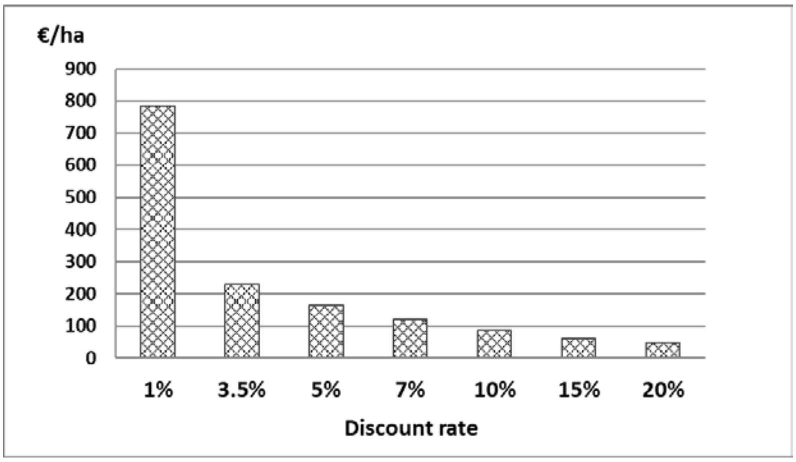

Figure 2. The average marginal value to farmers of conserving their soil natural capital in the study region for increasing discount rates (based on an assumed 1% relative change in the current, average stock of soil natural capital).

These valuations of changes in soil natural capital represent the change in the farmers' wealth, and hence long-term welfare, resulting from the implied changes in flows of supporting ecosystem services. Recall that the discount rate reflects the farmer's subjective valuation of future benefits. The lower the farmer's regard for the future, as indicted by the higher discount rates, the less they will value changes in their soil natural capital. Given that the social rate of discount lies between 1-3.5% and farmers' rates are likely higher, then farmers' valuations of changes in soil natural capital will be lower than that for society, resulting in an intertemporal externality. That is farmers, even given perfect information about the value of their natural capital, will most likely conserve lower stocks than is desirable from society's perspective.

Further, it is important to realise that our valuation does not consider the resilience or insurance value to farmers of conserving higher levels of soil natural capital (Cong, et al., 2014), thus our valuation is still likely underestimating the full value to farmers, which we return to in the discussion.

1.6 Regional level

The first step towards valuing changes in flows of public-good ecosystem services is to quantify and aggregate these at a relevant spatial scale such as the region we focus on here. To evaluate the impact of the three alternative soil management scenarios on farmers' incomes and public-good ecosystem services we simulated them using the AgriPoliS model.

The impacts of the three alternative management scenarios on the region's carbon stock, nitrogen emissions to the Baltic Sea, yields, N fertilizer input and average farm profits are presented in Table 3 compared to the reference scenario at the end of the simulation period. As expected public-good services in the form of carbon storage increase, and nutrient emissions and N input decrease substantially with the proportion of grass in the rotation. Initially, average farm profits also decrease substantially, by 18% in the 25% grass scenario, due to the large opportunity cost of lost crop production. However, over time, the improvements in soil productivity brought about by the investments in soil natural capital implied by the grass scenarios, result in this impact diminishing to 1% and less by 2036. By the end of the simulation period, 2036, only a small reduction in farm profits is predicted. This implies that farmers' costs of conserving soil carbon represent in fact investments in soil natural capital, which is repaid over time through the associated increase in supporting ecosystem services boosting soil productivity. Together, these results indicate the potential for investments in soil natural capital today to balance environmental concerns with future food production needs on the one hand, and farmers' livelihoods on the other.

Table 3. Changes in regional carbon stock, annual nitrogen emissions to the Baltic Sea, N fertilizer input and average yield of winter wheat in 2036 compared to the reference scenario.

	Carbon stock 2036	**Annual N-emissions** 2036	**Total N-input** 2036	**Ave. Yield**[1] 2036
Level in 2016	1.48×10^6 t	4.2×10^3 t	22×10^3 t	7.9 t
5% Grass	1.5 %	-2.8 %	-5.8 %	0.7 %
15% Grass	4.7 %	-8.3 %	-17.1 %	2.0 %
25% Grass	7.8 %	-13.7 %	-28.4 %	3.4 %

Source: Results of AgriPoliS simulations. Notes: [1)] Based on the average yield for winter wheat, as it is the predominant crop.

The simulated changes in agricultural productivity (Table 2) also imply a change in the underlying value of the region's soil natural capital and hence future food security. All three alternative scenarios generated a higher value of the region's soil natural capital than the reference scenario and over the range of tested discount rates (Figure 4): the assumed social rate of discount of 3.5%, and a lower (1%) and higher (5%) rate. As the scenario with 25% grass maintained the highest levels of supporting ecosystem services as indicated by SOC content, it also conserved the highest stock of soil natural capital and hence contribution to future food security. As expected the magnitude of the valuation of the change in future food security is highly sensitive to the choice of discount rate. To put these valuations in perspective the current market value of arable land in the region is around 23 000 €/ha (SCB, 2018), implying potentially substantial changes in farmers' wealth due to changes in supporting ecosystem services.

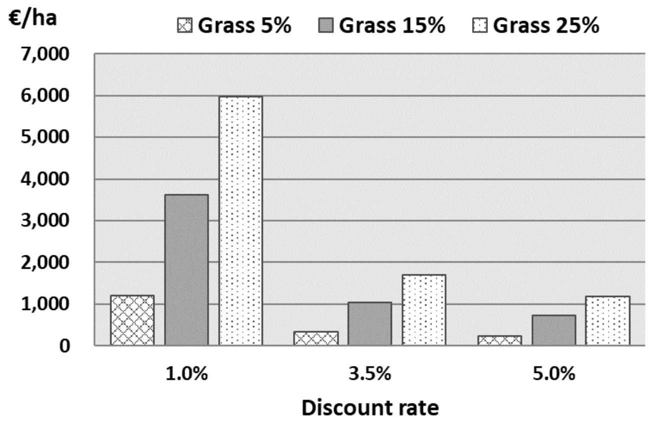

Figure 3. Average changes in the value of the region's stock of soil natural capital compared to the reference scenario for a range of discount rates over the 20 year evaluation period.

1.7 National level

The simulated changes in the indicators of public-good ecosystem services compared to the reference scenario, were convereted to their monetary values using both the low and high valuations of public goods (Table 4). Since each of the alternative management scenarios resulted in higher levels of public-good services over the evaluation period compared to the reference scenario, they also result in higher values of public-good services. The higher the proportion of grass in the alternative management scenario and assumed marginal valuation, Low or High scenario, the higher the valuation of the impact on each public-good service.

The large differences between the Low and High valuations of public-good services reflects the uncertainty associated with the marginal valuations of these services, which is why we perform the evaluation on societal welfare below considering this uncertainty.

Table 4. Impacts on societal welfare of increased flows of public-good ecosystem services compared to the reference scenario (Present values calculated in € millions over the 20 year simulation period and using a social rate of discount of 3.5%). Note: P-G refers to the assumed marginal valuations of the public-good ecosystem services.

Grass scenario	Carbon storage P-G valuations		GHG emissions P-G valuations		N emissions P-G valuations		Total P-G valuations	
	Low	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*
5 %	2.4	45.2	0.4	18.0	0.4	7.0	3.2	70.2
15 %	7.2	136.5	1.3	53.8	1.1	20.9	9.6	211.1
25 %	12.0	227.6	2.1	87.9	1.8	34.5	15.9	350.0

Finally, to evaluate the net impact of the grass scenarios on societal welfare we sum, according to Eq. (11), the net present values of the costs and benefits to farmers of implementing the scenarios (Farmer profits) with the additional benefits to society in the form of the increased levels of public-good services (Table 5). Although farmers benefit from reduced costs for fertilizers and higher optimal yields over time, the opportunity costs of increasing the area of grass in the crop rotation are higher, hence the net negative impact on farmers' profits. The valuation of the change in farmers' soil natural capital is not included in the calculation of Farmers' profits, but is included in the impact on future food security.

The net effect on societal welfare is positive in all scenarios and for all valuations of public good services (Table 5). In particular there emerges a substantial trade off between future food security or future generations' welfare, and current-generation farmers' profits. Applying the Low valuations of public good services and higher rates of discounts favours the production of private good ecosystem services over provisioning of public good services. Consequently, farmers are not likely to be optimizing their soil management decisions from Swedish society's perspective, implying a need for improved governance.

Table 5. Impacts on societal welfare of the alternative soil management scenarios (Net present values over 20 years in € millions and using a discount rate of 3.5%). Note: P-G refers to the assumed marginal valuations of the public-good ecosystem services).

Impacts on welfare	**Low P-G valuations**			**High P-G valuations**		
- *Grass scenario*	*5%*	*15%*	*25%*	*5%*	*15%*	*25%*
Public-good ecosystem services	3.2	9.6	15.9	70.2	211.1	350.0
Future food security	25.2	74.9	123.7	25.2	74.9	123.7
Farmers' profits	-21.5	-75.3	-132.7	-21.5	-75.3	-132.7
Net change in societal welfare	**6.9**	**9.2**	**6.9**	**73.9**	**210.8**	**341.0**

4 Discussion

We have developed and applied a road map for evaluating the contribution of private- and public-good ecosystem services generated by agricultural soils to human welfare. The approach considers the needs of decision-makers at different levels, specifically farmers and policymakers representing society.

If farmers are to be expected to change their soil management practices, it is essential that they can quantify the potential impacts of alternative practices on their economic welfare, since farming is their livelihood. Consequently, our road map begins with a practical method for quantifying the impacts of changes in flows of soil ecosystem services on farmers' wealth as inherent in the value of their soil natural capital. The method is based on an indicator of changes in flows of supporting and regulating ecosystem services that is suitable for economic valuation: the *relative* change in SOC content brought about by alternative management practices. Whether to invest in natural capital is one of the most difficult decisions faced by a farmer, because it involves certain expenditures and uncertain benefits in the future. With help of the approach developed here, farmers can quantify the long-term economic benefits of investing in soil natural capital.

Policymakers on the other hand have a broader, societal perspective and therefore need to consider the impacts of different soil management practices on public-good services as well. It is highly unlikely that markets will exist for public-good services and disseminate information of their value, as is the case for private goods such as agricultural commodities. Accordingly, policymakers are in need of methods to evaluate the contribution of public-good soil ecosystem services to societal welfare. As we show here, economic valuation of changes in flows of public-good ecosystem services makes it possible to systematically evaluate the impacts of different management practices on societal welfare; and thereby provide decision support for optimizing trade-offs with private-good services, and designing efficient governance systems. Indeed our Swedish case shows that the marginal value of conserving soil natural capital diverges substantially depending on the level of decision-making: farmers or society. Consequently, *if the societal value of soils is to be maximized farmers need to be provided with incentives to consider the value of public-good services in their management decisions*.

5 References

Adhikari, K., and A.E. Hartemink. 2016. "Linking soils to ecosystem services — A global review." *Geoderma* 262:101-111.

Ahlvik, L., and H. Ahtiainen. "Marginal benefits of reducing nutrient loads to the Baltic Sea." MTT Agrifood Research Finland & City of Helsinki, EU Life+ project CITYWATER - Benchmarking water protection in cities.

Ahtiainen, H., J. Artell, M. Czajkowski, B. Hasler, L. Hasselström, A. Huhtala, J. Meyerhoff, J.C.R. Smart, T. Söderqvist, M.H. Alemu, D. Angeli, K. Dahlbo, V. Fleming-Lehtinen, K. Hyytiäinen, A. Karlõševa, Y. Khaleeva, M. Maar, L. Martinsen, T. Nõmmann, K. Pakalniete, I. Oskolokaite, and D. Semeniene. 2014. "Benefits of meeting nutrient reduction targets for the Baltic Sea – a contingent valuation study in the nine coastal states." *Journal of Environmental Economics and Policy* 3(3):278-305.

Alvarez, R. 2005. "A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage." *Soil Use and Management* 21(1):38-52.

Arrow, K., M. Cropper, C. Gollier, B. Groom, G. Heal, R. Newell, W. Nordhaus, R. Pindyck, W. Pizer, P. Portney, T. Sterner, R.S.J. Tol, and M. Weitzman. 2013. "Determining Benefits and Costs for Future Generations." *Science* 341(6144):349-350.

Atkinson, G., I. Bateman, and S. Mourato. 2012. "Recent advances in the valuation of ecosystem services and biodiversity." *Oxford Review of Economic Policy* 28(1):22-47.

Balmann, A. 1997. "Farm-based modelling of regional structural change: a cellular automata approach." *European Review of Agricultural Economics* 24:85-108.

Barrios, E. 2007. "Soil biota, ecosystem services and land productivity." *Ecological Economics* 64(2):269-285.

Blair, N., R.D. Faulkner, A.R. Till, M. Körschens, and E. Schulz. 2006. "Long-term management impacts on soil C, N and physical fertility: Part II: Bad Lauchstadt static and extreme FYM experiments." *Soil and Tillage Research* 91(1–2):39-47.

Blombäck, K., H. Johnsson, A. Lindsjö, K. Mårtensson, K. Persson, and F. Schmieder. "Leaching of nutrients from Swedish arable land (In Swedish: Läckage av näringsämnen från svensk åkermark för år 2009 beräknat med PLC5-metodik)." Swedish Meteorological and Hydrological Institute.

Bommarco, R., D. Kleijn, and S.G. Potts. 2013. "Ecological intensification: harnessing ecosystem services for food security." *Trends in Ecology & Evolution* 28(4):230-238.

Bostedt, G., S. Löfgren, S. Innala, and K. Bishop. 2010. "Acidification Remediation Alternatives: Exploring the Temporal Dimension with Cost Benefit Analysis." *Ambio* 39(1):40-48.

Bouma, J. 2019. "Soil Security in Sustainable Development." *Soil Systems* 3(1):5.

Brady, M., C. Sahrbacher, K. Kellermann, and K. Happe. 2012. "An agent-based approach to modeling impacts of agricultural policy on land use, biodiversity and ecosystem services." *Landscape Ecology* 27(9):1363-1381.

Brady, M.V., K. Hedlund, R.-G. Cong, L. Hemerik, S. Hotes, S. Machado, L. Mattsson, E. Schulz, and I.K. Thomsen. 2015. "Valuing Supporting Soil Ecosystem Services in Agriculture: A Natural Capital Approach." *Agronomy Journal* 107(5):1809-1821.

Brunell, J.T., H. Gustavsson, J. Dahné, and G. Alavi. "Retention calculated with SMEDHYPE (In Swedish: Retention beräknad med SMEDHYPE)." Swedish Meteorological and Hydrological Institute.

Brunstad, R.J., I. Gaasland, and E. Vårdal. 2005. "Multifunctionality of Agriculture: An Inquiry into the Complementarity between Landscape Preservation and Food Security." *European Review of Agricultural Economics* 32(4):469-488.

Burton, R.J.F., and G. Schwarz. 2013. "Result-oriented agri-environmental schemes in Europe and their potential for promoting behavioural change." *Land Use Policy* 30(1):628-641.

Carbon Pulse (2016) EU Market: EUAs stumble despite strong auction, with observers mixed on next move. https://carbon-pulse.com/25840/.

Cassman, K.G., A. Dobermann, D.T. Walters, and H. Yang. 2003. "Meeting Cereal Demand While Protecting Natural Resources and Improving Environmental Quality." *Annual Review of Environment and Resources* 28:315-358.

Cong, R.-G., H.G. Smith, O. Olsson, and M. Brady. 2014. "Managing ecosystem services for agriculture: Will landscape-scale management pay?" *Ecological Economics* 99:53-62.

Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R.V. O'Neill, J. Paruelo, R.G. Raskin, P. Sutton, and M. van den Belt. 1997. "The value of the world's ecosystem services and natural capital." *Nature* 387:253-260.

Crost, B., and C.P. Traeger. 2014. "Optimal CO2 mitigation under damage risk valuation." 4:631.

Daily, G.C., S. Polasky, J. Goldstein, P.M. Kareiva, H.A. Mooney, L. Pejchar, T.H. Ricketts, J. Salzman, and R. Shallenberger. 2009. "Ecosystem services in decision making: time to deliver." *Frontiers in Ecology and the Environment* 7(1):21-28.

De Nocker, L., S. Vermoote, and T. Heck (2004) Valuation of environmental impacts based on preferences revealed in political negotiations and public referenda, ed. R. Friedrich. Stuttgart, University of Stuttgart, pp. 119-148.

Field, B.C. 1997. *Environmental Economics: An Introduction*. New York: McGraw-Hill.

Government Offices of Sweden. "Sweden’s carbon tax ". Government Offices of Sweden.

Happe, K., K. Kellermann, and A. Balmann. 2006. "Agent-based Analysis of Agricultural Policies: an Illustration of the Agricultural Policy Simulator AgriPoliS, its Adaptation and Behavior." *Ecology and Society* 11(1):49 [http://www.ecologyandsociety.org/vol11/iss41/art49/].

HELCOM. "State of the Baltic Sea – Second HELCOM holistic assessment 2011-2016."

Höjgård, S., and F. Wilhelmsson. "Produktion av biogas från gödsel." AgriFood Economics Centre.

Hristov, J., M.V. Brady, C. Dong, A. Sahrbacher, and C. Sahrbacher. "Representation of the Scanian regions GMB and GSS in AgriPoliS and recent model extensions." AgriFood Economics Centre [http://www.agrifood.se/].

HS. "Soil organic carbon database." The Rural Economy and Agricultural Societies (Hushållningssällskapen).

Kellermann, K., K. Happe, C. Sahrbacher, A. Balmann, M. Brady, H. Schnicke, and A. Osuch. "AgriPoliS 2.1 - Model Documentation." IAMO, 06/10/17.

Kirchmann, H., L. Bergström, T. Kätterer, L. Mattsson, and S. Gesslein. 2007. "Comparison of Long-Term Organic and Conventional Crop–Livestock Systems on a Previously Nutrient-Depleted Soil in Sweden." *Agronomy Journal* 99(4):960-972.

Lal, R. 2010. "Managing Soils and Ecosystems for Mitigating Anthropogenic Carbon Emissions and Advancing Global Food Security." *Bioscience* 60(9):708-721.

---. 2014. "Societal value of soil carbon." *Journal of Soil and Water Conservation* 69(6):186A-192A.

Luo, Z., E. Wang, and O.J. Sun. 2010. "Soil carbon change and its responses to agricultural practices in Australian agro-ecosystems: A review and synthesis." *Geoderma* 155(3–4):211-223.

McConnell, K.E., and N.E. Bockstael (2005) Valuing the Environment as a Factor of Production, ed. K.-G. Mäler, and J.R. Vincent. Amsterdam and San Diego, North-Holland.

Mueller, N.D., J.S. Gerber, M. Johnston, D.K. Ray, N. Ramankutty, and J.A. Foley. 2012. "Closing yield gaps through nutrient and water management." *Nature* 490(7419):254-257.

Nelson, E., G. Mendoza, J. Regetz, S. Polasky, H. Tallis, D.R. Cameron, K.M. Chan, G.C. Daily, J. Goldstein, P.M. Kareiva, E. Lonsdorf, R. Naidoo, T.H. Ricketts, and M.R. Shaw. 2009. "Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales." *Frontiers in Ecology and the Environment* 7(1):4-11.

OECD. 2001. *Valuing Rural Amenities*. Paris, France: OECD Publishing.

Pimentel, D., P. Hepperly, J. Hanson, D. Douds, and R. Seidel. 2005. "Environmental, Energetic, and Economic Comparisons of Organic and Conventional Farming Systems." *Bioscience* 55(7):573-582.

SCB. "Agricultural land prices 2017." Statistics Sweden.

---. "Standard yields for yield survey districts, counties and the whole country in 2013 (In Swedish, Normskördar för skördeområden, län och riket 2013)." Statistics Sweden.

Shortle, J., and R.D. Horan. 2017. "Nutrient Pollution: A Wicked Challenge for Economic Instruments." *Water Economics and Policy* 03(02):1650033.

Sidemo-Holm, W., H.G. Smith, and M.V. Brady. 2018. "Improving agricultural pollution abatement through result-based payment schemes." *Land Use Policy* 77:209-219.

Simmelsgaard, S.E. 1998. "The Effect of Crop, N-Level, Soil Type and Drainage on Nitrate Leaching from Danish Soil." *Soil Use and Management* 14:30-36.

Simmelsgaard, S.E., and J. Djurhuus. 1998. "An empirical model for estimating nitrate leaching as affected by crop type and the long-term N fertilizer rate." *Soil Use and Management* 14(1):37-43.

Sunderland, T.C.H. 2011. "Food security: why is biodiversity important?" *International Forestry Review* 13(3):265-274.

Svensson, M., and L. Hultkrantz. 2014. "Ekonomiska utvärderingar i svensk offentlig sektor – likheter och skillnader." *Ekonomisk debatt* 43(3):40-50.

Thomsen, I.K., and B.T. Christensen. 2004. "Yields of wheat and soil carbon and nitrogen contents following long-term incorporation of barley straw and ryegrass catch crops." *Soil Use and Management* 20(4):432-438.

Tilman, D., K.G. Cassman, P.A. Matson, R. Naylor, and S. Polasky. 2002. "Agricultural sustainability and intensive production practices." *Nature* 418(6898):671-677.

Warren, R. 2014. "Optimal carbon tax doubled." *Nature Climate Change* 4(July):534-535.

Wulff, F., C. Humborg, H.E. Andersen, G. Blicher-Mathiesen, M. Czajkowski, K. Elofsson, A. Fonnesbech-Wulff, B. Hasler, B. Hong, V. Jansons, C.-M. Mörth, J.C.R. Smart, E. Smedberg, P. Stålnacke, D.P. Swaney, H. Thodsen, A. Was, and T. Żylicz. 2014. "Reduction of Baltic Sea Nutrient Inputs and Allocation of Abatement Costs Within the Baltic Sea Catchment." *Ambio* 43(1):11-25.