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Evaluating profitability of soil-renovation investments under crop rotation constraints in Finland

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ABSTRACT

Increasing the resource use efficiency of agricultural production is considered as a central element in Sustainable Intensification (SI) of agriculture, which is a promising strategy to satisfy increasing demand for food while reducing negative impacts on farm economy and environment. One challenge for SI is that degradation of agricultural soils and resulting crop yield losses are affecting negatively farmers' incomes and environment. This study analyses economic profitability of soil renovation investments aimed for tackling soil compaction in a regional context of south-west Finland, where some individual land parcels are compacted on many farms, implying crop yield losses, which we assume as −30%. We use a dynamic optimisation farm model with multiple input-use responses on crop yields. Explicit field parcel-specific crop-rotation constraints are accounted for in solving the farmers' decision problem of soil-renovation investments. Our results calculated over a 30 year time period suggest that soil-renovation investments are profitable since they produce a positive net present value (NPV) assuming 2000–2014 average crop prices, at all discount rates up to 10% when 30% yield decrease due to soil compaction is assumed. Higher than average crop prices would increase the value of soil renovation investment significantly while lower than average future crop prices would have a relatively small effect on the profitability of soil-renovation investment. The payback times of soil-renovation investments are approximately 8–11 years, depending on the discount rate, but largely independent on crop prices. Soil renovation increases production of higher valued crops, but the utilisation of the whole production potential of a farm is dependent on crop prices. We found that the full increased production potential may not be utilized after the renovation investment if not utilized already without the investment. It is concluded that one may recommend soil-renovation investments as a profitable long-term investment in a typical case, but one cannot recommend the soil renovation if no significant yield gains are possible, or if only low valued crop are to be produced. Nevertheless the field parcel-specific restrictions to avoid soil compaction after the renovation are important to be accounted for in evaluating the profitability of soil renovation at the farm level, since avoiding soil compaction is one part of more sustainable production strategy.

1. Introduction

Farmers typically have field parcels with different productivity levels. If soil quality and productivity in individual field parcels can be influenced by farm level actions, a farmer faces a decision problem: Is it economically profitable to invest in soil improvements? What are the management implications? It is not easy to evaluate the profitability of soil-renovation investments, since they can be closely linked to the choice of crop rotation and other constraints with dynamic consequences for a farm. Furthermore, future earnings from higher crop yields are dependent on uncertain future crop prices.

This problem of farmers has wider societal, environmental and market implications. Food demand is gradually increasing globally and responding to that challenge is not trivial (Godfray et al., 2010). Sustainable intensification of agriculture is seen as an important strategy to respond to increased global food demand and to improve the environmental effects of agriculture (Tilman et al., 2011). This is hardly possible without increasing the effective utilisation of farming inputs. Since inputs such as fertilisers are poorly utilized and can lead to nutrient leaching if soil is degraded, soil improvement is one important aspect of sustainable intensification (Soanea and van Ouwerkerk, 1995).

Another, related motivation for soil improvements is linked to climate change. More frequent extreme weather conditions such as droughts or floods, pose adaptation challenges for farmers. These

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challenges are related to soil functions and quality (Hamidov et al., 2018). Improved soil structure could alleviate the effects of more frequent extreme weather conditions (Peltonen-Sainio et al., 2016). This is particularly relevant in Northern Europe where increased precipitation is a likely outcome of climate change (Ruosteenoja et al., 2011). Adaptation to climate change, if successful, could increase crop yields in Northern Europe (Höglind et al., 2013; Rötter et al., 2013). However, significant yield gaps (difference between potential and actual yield) have also been observed in the past few decades in Northern Europe, and they are increasing rather than decreasing (Palosuo et al., 2015; Peltonen-Sainio et al., 2015). Decreasing yield gaps through nutrient and water management are strongly linked to soil structure (Mueller et al., 2012).

Whole-farm modelling, including comprehensive land use and nutrient-use descriptions, has been considered important when analysing improvements in sustainability of farming systems. During the last decade, dynamic whole-farm modelling has been used in farm-level analysis for example in nutrient dynamics analysis (Berntsen et al., 2003; Chardon et al., 2012; Dueri et al., 2007; Vogeler et al., 2013). The whole-farm approach is also relevant here since renovation investments affect farm management, for example how fields of different yield potential are cultivated.

The aim of this paper is to evaluate the economic profitability of soil-renovation investments in Finland, located in Northern Europe. We show how a dynamic farm level optimisation model with crop yield responses from multiple inputs and explicit crop-rotation effects and constraints is used in solving farmers' decision problems concerning soil-renovation investments. We calculate net present value and payback time of soil-renovation investments taking into account the farm management decisions including crop rotations per field plot and the use of inputs per field plot and crop.

Soil structure deterioration due to soil compaction is a common farm management related source of crop yield losses. To be able to analyse the profitability of soil-renovation investments of compacted soils, we need to understand why and how compacted soils can be renovated.

Compaction is caused when internal or external loads press soil particles together, reducing the pore space between them. When the size of pores decreases, water infiltration and drainage decrease and the exchange of gases slows down. Soil compaction impedes root growth, which in turn decreases a plant's ability to take up nutrients and water, and might lead to nitrogen and potassium deficiency. Depending on the circumstances of the growing season, soil compaction can cause different problems. Wet conditions decrease soil aeration, which results in increased denitrification. On the other hand, plants growing in compacted soil are more susceptible to drought stress during dry seasons because of decreased root growth (Alakukku, 2012; Tracy et al., 2011).

Hoefer and Hartge (2010) listed four main reasons for subsoil compaction; (1) Water impact, which is a natural phenomenon, (2) intensive or continuous tillage operations within the same depth in the soil, (3) lack of crop rotation which can limit rooting systems in the soil, and as the main reason, (4) impact of machinery load. Compaction is more severe the heavier the axle loads of machines are and the more frequent the traffic is. Soil moisture content is a key determinant of the level of compaction when the field is trafficked. The weight of agricultural machines has increased considerably in Finland during the last 20–30 years due to increasing farm sizes. Some adaptation strategies to minimise compaction are controlled traffic, reduced machinery size and reduced ground pressure using tracked machinery. (Alakukku et al., 2003; Håkansson et al., 1987; Van Den Akker et al., 2003).

Chamen et al. (2015) reviewed soil compaction effects on crop yields in different studies. Yield reduction varied a great deal between studies depending on the crop, country, soil type and year the study was published (1978–2003). The most extreme yield reduction was close to 50%, whereas most of the yield reductions were found to be 15–30%. Review of Chamen et al. (2015) contained a study of McAfee et al. (1989) where yield decrease of oats caused by compaction was estimated to be 30% in Uppsala area in Sweden where growing conditions are quite similar to south-west Finland. Håkansson et al. (1985) estimated yield losses because of soil compaction in 26 different test sites in Northern Europe, The Netherlands, Canada (Quebec) and the U.S.A. (Minnesota and Wisconsin). Estimated average yield loss varied between 15 and 20%.

Mechanical deep loosening of soil, also called subsoiling, is one possible solution for problems related to compacted soil. The aim is to break and loosen the condensed layer of the soil. This should improve the water conductivity, the structure of the soil and the utilisation of nutrients. A subsoiler (also called flat lifter) is usually mounted to a tractor. A subsoiler will break up and loosen soil to a depth of 25–30 cm.

After subsoiling, the stability of the soil is low and there is a risk of recompaction. If cultivation continues the same way as before subsoiling, recompaction can re-emerge within 3–5 years and might become even denser than before loosening (Alakukku, 2012; Horn et al., 1995). To ensure the benefits of subsoiling persist for a longer period of time, it is important that grass crops or other deep-rooted crops are grown during the first years after subsoiling. After this, deep-rooted crops should regularly be included in the crop rotation to maintain the benefits of subsoiling (Peltonen-Sainio et al., 2016; Spoor et al., 2003).

Chamen et al. (2015) estimated the costs and benefits of soil compaction mitigation practices based on UK examples and soil types. Targeted subsoiling resulted in a positive gross margin change between £0/ha for sandy soils and £22/ha (≈25€/ha) for clay soils for winter wheat. Targeted subsoiling was seen as the most profitable alleviation management for subsoil compaction.

Jin et al. (2007) studied the effects of subsoiling on maize and wheat yields in northern China. In an eight-year period yields increased 10–12% on average when subsoiling was accompanied with 4-year no-till planting operation maintaining soil cover. Economic benefits were considerable. Farmer income increased 49% in the case of maize and 210% in the case of wheat due to subsoiling. It is worth taking into account that in the study of Jin et al. (2007) changes occurred also in other farming practices in addition to subsoiling compared to the base scenario with no subsoiling.

Grevers and Taylor (2013) found subsoiling to be profitable at low crop prices but unprofitable with very low prices at drylands in Saskatchewan, Canada with discount rates 5–10%.

In our analysis we outline how the soil-renovation investment could be implemented. We then analyse the profitability of the renovation, considering farm management and land use, as well as production and farm income implications in detail. We account for logistics costs due to distances to different field parcels and calculate greenhouse gas emissions. We discuss the results and conclude on their meaning for farmers and policy makers.

2. Materials and methods

2.1. Study region

Our analysis and modelling is implemented assuming typical production conditions, use of inputs and average crop yields in Varsinais-Suomi province located in south-west Finland. This region is among the most favourable agricultural regions in Finland, but the crop yields (cereals approximately 4 tons/ha) are still significantly lower than in many countries in western and central Europe. In the period 1981–2010, the average length of the thermal growing season was 180–200 days. The effective temperature sum was 1300–1450 degrees, and the average precipitation in the growing season was 350–400 mm (Pirinen et al., 2012). The growing season usually starts in the last week of April and ends at the end of October. 55% of farms are cereal farms in this region (Tike, 2014). The average size of all farms in 2011 was 45.75 ha (Tike, 2012). Most farms in the region apply short crop rotations or monocropping (Vuorio et al., 2006). Varsinais-Suomi cereal farms are affected by the 5% minimum area requirement for an ecological area under the EU's CAP (set-aside is accepted as an ecological area), and by the maximum area restriction (15%) under nature management fields (NMF) and maximum overall set-aside area (set-aside and NMF) restriction (25%), as specified in the CAP agri-environmental scheme implemented at the national level. The dominant soil types in the region are clay and coarse textured mineral soils such as fine silt, loam and coarse sand (Lemola et al., 2018). Soil compaction on such soil types is common at some individual field parcels at many farms in the region (Maaseudun Tulevaisuus, 2015). However, the causes of soil compaction are field parcel specific and soil type as such is not the primary cause of soil compaction (ibid).

2.2. DEMCROP model

To study the profitability of soil renovation in the Varsinais-Suomi region, we utilise a dynamic economic model of farm management and crop rotation (DEMCROP), applied earlier in studies of Lehtonen et al. (2016, 2014) and Liu et al. (2016), and most recently in Purola et al. (2018). This study is based on the application of the DEMCROP model further developed and presented by Purola et al. (2018). By utilising dynamic optimisation, DEMCROP can handle dynamic inter-temporal decisions together with short-term decisions. This model maximises discounted expected future gross margin of a farm minus weighted covariance of the gross margin - according to the classic mean-variance model - assuming that risk-averse farmers make trade-offs between expected profit and variance of profit. To do so, a farmer can adjust annual land allocation - both in overall and at a parcel specific level - as well as crop rotation over several years, and annual input use (fertilising, liming, fungicide) considering given input and output prices, degree of risk aversion and policy restrictions.

The model comprises farm-level dynamic optimisation over a 30-year time span which can well accommodate the dynamics of soil pH and liming and crop rotation choices and effects on yields, as well as the effects of nitrogen fertilisation and fungicide use on crops.

DEMCROP can be formulated and solved by nonlinear programming as follows:

$$Max \sum_{t=1}^{30} \sum_{p}^{10} \sum_{i=1}^{M} \frac{1}{(1+r)^t} (Y(A(p,t,i),p,t,i)A(p,t,i)P(i) + S(i) - C(p,t,i)) - \theta \sum_{t-1}^{H} \sum_{c} \sum_{c2} \frac{1}{(1+r)^t} A'XA \quad (1)$$

subject to

$$\sum_{\forall i} A(p,t,i) = 1,$$

where $A(p,t,i)$ is area allocation for crop i on time (year) t at field parcel p. $Y(\cdot)$ is crop yield level, dependent on nitrogen fertilisation level (which, in turn, depends on expected crop and fertiliser prices), past area allocations on field parcel p (there are yield losses due to monocultural cultivation). $P(i)$ is expected average market price of crop i, $S(i)$ is subsidy paid per hectare, and $C(\cdot)$ is cost per hectare. X is covariance matrix of crop specific gross margins calculated based on crop yields and prices of inputs and outputs during 2000–2014. This means that past co-variation of the gross margins are assumed while expected average market prices of crops are fixed. Gross margins of all cereals are highly positively correlated while the gross margin of oilseeds is positively but relatively less correlated with the gross margins of cereals, and gross margin of set-aside is little correlated with any crops (see Table A3 in supplementary materials). There are no negative correlations between any crops or set-aside. Hence we assume no change in the covariation of gross margins. There is 1 unit of farmland available at the farm. A discount rate (r) of 6% has been used. The model is presented in more detail by Purola et al. (2018).

The main features of the model, modified for this case, can be summarised as follows. The farm is split into 10 equally sized (5 ha) and shaped field parcels. The distance from parcels to the farm centre varies between 0 and 7 km, averaging 3 km. 9 field parcels are assumed to be of a mineral soil type, which is the dominant soil type in the region. Initial yields in these parcels are assumed to be the average yields in the region 2000–2014. One parcel out of ten is of an organic soil type and the initial yield in this parcel is slightly lower. The farmer has eight land use options, six crops (spring wheat, winter wheat, feed barley, malting barley, oats and oilseed rape) and two types of set-asides (normal set-aside and nature management field). A fixed yield penalty matrix is created to include the effect of monoculture on crop yields, to be explained in more detail later. Crop and field parcel specific management decisions include liming, fertilisation and fungicide use decisions, in addition to land-use decisions for all field parcels. Soil pH, affected by liming decisions, affects crop yields in each field parcel. Nitrogen fertilisation is crop specific and is optimised based on input and output prices. Mineral nitrogen fertilisation decreases the soil pH every year, which means that liming is required to reach or maintain the optimal pH.

Liming is a dynamic decision since choosing a higher amount of liming can raise the soil pH to an optimal level immediately, but it will take several years before soil pH decreases to low levels again. A minimum level of 5.5 is given for soil pH in mineral parcels and 5.0 in organic soil type parcel to prevent very low soil pH and crop yield levels since agricultural policy conditions require that land has to be kept in good agricultural condition (Lehtonen and Niemi, 2018).

Fungicide treatment is determined based on annual input and output prices and does not have dynamic consequences. Logistics costs related to the cultivation of each field parcel depend on crop and management choices and are calculated based on the distances between parcels and the farm centre. Logistics costs include driving times, fuel consumption and labour needs.

2.3. Input data

2.3.1. Historical yield and price data

Historical data comprises 15 years (2000–2014) for crop yields, variable costs and subsidy data. Crop yields are extracted from official farm statistics (OFS, 2018) for the Varsinais-Suomi region in Finland (Table 1). The average crop yield per crop, used in validating the DEMCROP model in the baseline scenario to be presented below, is the mean value of the annual yield over 15 years obtained from official agricultural statistics of Finland (OFS, 2018). The average variable costs and subsidies of the crops are derived from a recent version of a dynamic regional sector model of Finnish agriculture (DREMFIA) (Lehtonen, 2001; Lehtonen and Niemi, 2018), which relies on validated approximations of the average use of inputs per crop in each region.

Table 1
Input data used in the DEMCROP model. Source: OFS, 2018 (average yields); DREMFIA sector model (Lehtonen and Niemi, 2018) (variable cost, subsidy per ha). Average input data consisting of crop yields, variable costs and subsidies used in the model.

Crop	Average yield kg/ha	Variable cost €/ha	Subsidy €/ha
	$Y_{MEAN}(p, c^i)$	$C_{variable}(c^i)$	$S(c^i)$
Spring wheat	3720	580	650
Winter wheat	3896	610	682
Feed barley	3814	527	563
Malting barley	3815	589	635
Oats	3807	510	563
Oilseed rape	1734	587	705
Set-aside	–	234	390
NMF[a]	–	244	554

[a] Nature management field.

2.3.2. Parameters for fungicide treatment and liming

Fungicide treatment efficiency is based on field trial estimates in various locations around Finland in 1999–2010 in the case of barley (Purola, 2013) and 1999–2013 in the case of wheat by using the same estimation methods. On average, efficient fungicide treatment can increase yields by 11.7% (wheat) and 12.7% (barley). However, we acknowledge that the crop yields measured in the field trials are often clearly higher (e.g. 6 ton/ha) than the average crop yields at actual farms (< 4 tons/ha) (Peltonen-Sainio et al., 2015). Thus we consider estimated yield effects of fungicide use to be less effective on average cereal farms. Based on our fungicide use response functions in the model, a farmer can increase the yields by 5.85% (wheat) and 6.35% (barley) temporarily for one year if using fungicides. The costs of fungicide spreading are assumed to equal the price of contractor work (price lists publically available).

The pH values of Finnish agricultural soils commonly lie between 4.5 and 6.5, while the most beneficial pH range for most plants is 6.5–7.5. Inorganic nitrogen fertilisation has a tendency to decrease soil pH values. Counterbalancing this, the DEMCROP model includes a liming activity which increases soil pH. Increasing soil pH by one unit increases crop yields by 10–15%, based on Myyrä et al. (2005). In this case, 9 parcels are a mineral soil type where pH can vary between 5.7 and 6.8. Parcel 6 is an organic soil type where the pH can vary between 5.0 and 6.4. The yield response for soil pH is assumed to be linear within this range and is similar for both soil types. The pH of soil in which the average yields are realized differs between crops and is based on cultivation recommendations (Farmit, 2019). In the model we assume that the pH values of soils are 6.1 in mineral parcels and 5.7 in organic soil type parcel at year one. The costs of liming activity have been derived from available sources on lime spreading contract operations.

2.3.3. Yield penalty matrix for monocultural cultivation

Yields decrease if the same crop or similar crops are cultivated in the same field parcel continuously without breaking the sequence with dissimilar crops. To take into account the effects of monocultural cultivation in the yields, the DEMCROP model keeps track of the cultivation history of each field parcel and includes a yield penalty matrix which defines a yield loss of 5% for cereals if the same cereal as the previous year is cultivated in the same field parcel the following year (see Liu et al., 2016 for details).

If one spring cereal follows another, but a different spring cereal crop, then a slightly lower yield loss of 4% is assumed. If oilseed rape is cultivated following oilseed rape in the same field parcel the previous year, a 25% yield loss is assumed. This is based on the empirical observation that oilseed rape diseases may still be prevalent in the soil three to four years after oilseed rape cultivation, but are largely absent after five years from the last oilseed rape cultivation (Peltonen-Sainio et al., 2007). The model keeps track of the five-year cultivation history of each field parcel. This five-year memory of cultivation history also implies that yield losses due to monoculture are cumulative over the five previous years, but do not accumulate any more over a longer time period than five years in the past. For example, accumulated monocultural yield losses of spring cereals may be close to 23%, if the same cereal crop is allocated in the same field parcel for five years in a row, but the yield loss does not accumulate further if there are six or more years of monoculture. However, cultivating cereals, oilseeds, grass or set-aside in a sequence of any order in the same field parcel eliminates yield losses of monoculture. Thus, the model has the opportunity of breaking monoculture by crop rotation. In the case of malting barley we have imposed some restrictions based on the requirements of malting barley quality and cultivation recommendations (VYR, 2014). Barley - either barley for feed or malting barley - should not be a pre-crop for malting barley. We also impose constraints that malting barley is not feasible in organic soils and in compacted soils because of uncertainty of nitrogen uptake.

2.4. Risk aversion coefficient

Some farmers are risk-averse, for example they prefer production plans leading to a more secure level of income, although it can mean a slightly lower average (expected) income compared to production plans with higher risks (Raskin and Cochran, 1986). One common risk management strategy is diversification of production. Diversification reduces the risk of volatile farm returns by mitigating price risk and volatility in crop output (yields of different crops are not perfectly correlated) and farm revenues, since it reduces reliance on only one market and exposure to its price fluctuations (Robison and Barry, 1987).

When maximising expected utility (*E*-U), linear mean-variance (E-V) with an exogenously specified risk aversion parameter has been a common way to model risk in mathematical programs (Petsakos and Rozakis, 2015).

Two common ways of representing farmer's risk attitudes are constant absolute risk aversion (CARA) and relative risk aversion (RRA). Absolute risk aversion does not take into account wealth effects on risk aversion, such as effects of farm income on wealth and resulting change in risk aversion is not accounted for whereas relative risk aversion (RRA) does. The value of RRA is obtained by multiplying ARA by wealth.

Raskin and Cochran (1986) reviewed empirically estimated Pratt-Arrow absolute risk aversion coefficients. Reviewed studies were made 1981–1986. Risk aversion for category "Almost risk neutral" varied between −0.00001 and 0.001 whereas range in category "Strongly risk averse" was 0.0005–0.0025. There are different considerations of the range of relative risk aversion in the literature. According to Ruixuan et al. (2011), the average relative risk aversion of farmers vary from 0 to 10. Kocherlakota (1996) considered values over five very unlikely and in a literature review Anderson and Dillon (1992) considered values 0–4 most likely.

It is hard to determine the actual wealth of farmers and how much overall wealth affects farmers' risk attitudes in Varsinais-Suomi region. However since many cereal farms in Varsinais-Suomi are part-time farms and most household income comes from off-farm (OSF, 2014), we have no reason to assume high risk aversion. According to Luke (2019) the average net worth (own capital) of field crop farms in Varsinais-Suomi region was 312,655 €. The average size of these farms was 57.6 ha.

Based on above classifications and data we chose 0.000002 as our absolute risk aversion parameter. This would mean that if we assume that the own capital of a farm as a wealth, the relative risk aversion coefficient would be 0.63. Only land allocations were affected by risk aversion coefficient. We solved the model using various risk aversion coefficients between 0 and 0.00002. Land allocations are presented in Fig. 1. It can be seen that land allocation does not different much when using low risk aversion coefficients.

2.5. Model validation

The most important step in our model validation was to ensure that the model results of crop yields and input use correspond to the observed reality in the Varsinais-Suomi region. This is because input use and crop yield levels greatly affect land use and farm income. We checked input and output prices as well farm subsidy information over the simulated model validation period 2000–2014 (sources given in Section 2.3.1). After that we simulated our DEMCROP model with the selected risk-aversion parameter. The model outcomes show that crop yields, soil pH, use of nitrogen and fungicides correspond to regional average levels (Appendix).

2.6. Scenario settings

We construct two soil management scenarios: compacted parcels

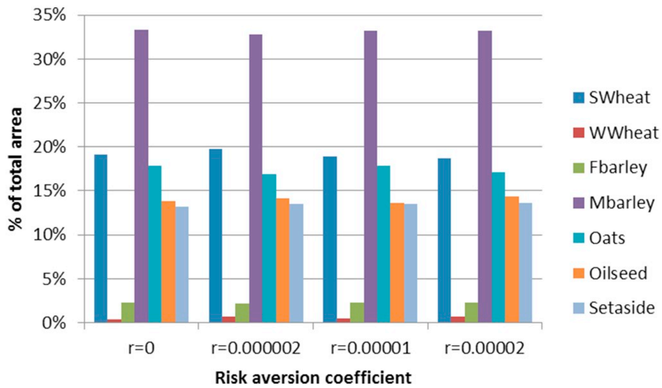

Fig. 1. Simulated average area coverage of selected crops with a range of risk aversion coefficients.

scenario with 30% crop yield reduction on 2 out of 10 field parcels, and renovation scenario where soil compaction and yields reduction is fixed. We analyse profitability of soil renovation at compacted parcels under three different crop price levels, making 6 different scenarios in total (Table 2). The average crop prices in Finland 2000–2014 are taken as baseline prices (BP). Sensitivity analysis is done assuming also 10% and 20% crop yield reduction at average crop prices, over a 30-year time span. We also analyse the sensitivity of the results by assuming different discount rates.

In the ***compacted parcels scenario (CP)*** we assume that parcels 3 (1 km from the farm centre) and 7 (3 km) are suffering from 30% decreased yields caused by soil compaction which is based on soil compaction studies review by Chamen et al. (2015) where yield decrease caused by soil compaction varied mostly between 15 and 30%. Taking into account that many of those studies were done many decades ago when the weight of agricultural machinery was lower, it is reasonable to assume yield losses from the upper limit of the range. This scenario is used as a reference to the renovation scenario (below). Sensitivity analysis to yield reductions caused by compaction are made simulating scenarios with −10% and − 20% yield decreases with base prices.

In the ***renovation scenario (RS)*** the farmer renovates the compacted soil parcels 3 and 7. Parcels are subsoiled in the first two years and in the first year wood fibre is also spread for soil improvement. The costs of these measures are 280 €/ha in the first year and 80 €/ha in the second year. Parcels 3 and 7 are under green manuring and cannot produce any market revenues during the first 3 years when the farmer receives a subsidy of 465 €/ha (subsidy for set-aside 290 + 75 €/ha for green manuring) for these parcels. We assume that these practices increase yields back to the same level as in the other parcels already after 3 years. To avoid re-compaction of the soil, deep-rooted crops (oilseed rape in this study) or grassland set-aside (normal or NMF) must be cultivated in the parcels on at least 3 years out of ten years every decade. This means that at least 30% of the area of parcels 3 and 7 must be allocated for oilseed rape or set-aside every decade - however the farm management simulated by the DEMCROP model can freely decide in which years this condition is fulfilled. This means that once parcels 3 and 7 are prone to compaction, these crop rotation restrictions are needed to avoid recompaction after the treatments of the three first years. These crop rotation restrictions limit the production possibilities at the farm.

Table 2
Price scenarios. Baseline = Average farm-gate crop prices paid in Finland 2000–2014. Source: OSF (2014).

Soil management scenario	Price scenario		
	Baseline −20%	Baseline	Baseline +20%
Compacted parcels (CP)	CP -20%	CP BP	CP +20%
Renovation (RS)	RS -20%	RS BP	RS +20%

It is assumed in all scenarios that there is a requirement that at least 5% of the farmland area of a farm must be a set-aside area (NMF or other set-aside). This is obligatory to meet ecological targets, for example water protection targets, for the Varsinais-Suomi region, as well as to maintain biodiversity. The maximum area of NMF is restricted to 15% and the total area of set-aside and NMF cannot exceed 25%. Current CAP rules for greening also restricts monocropping; the total area of two main crops cannot exceed 75% of the total land area.

2.7. Logic of the analysis

We analyse the profitability of soil compaction renovation - based on a comparison between the compacted parcels and renovation scenarios - by using net present value of future income. It is useful - not least from farmers' point of view - to present profitability results as changes in average gross margin per ha per year which is based on discounted NPV. We also calculate payback times. Renovation is considered to pay itself back in the year when the total discounted stream of gross margins exceeds the discounted value of gross margins under no-renovation (compacted parcels scenario).

Crop rotation restrictions play a role here: The first 3 years under green manure set-aside imply no market revenues from parcels 3 and 7, and after that, 3 out of 10 years must be allocated to oilseeds or set-aside in field parcels 3 and 7, every decade. These costs due to crop rotation requirements are difficult to be considered without the explicit crop rotation restrictions included in the DEMCROP model.

We are not evaluating the profitability of renovation based on one field parcel only. It is important to account for the changes in land use, input use and crop yields on the whole farm.

A farmer can allocate parcels that are in poor condition to set-aside, rather than take renovation investment and - at least in low-price conditions - may gain almost the same or even higher profit in the short run. On the other hand, renovation actions leading to improved crop yields in compacted soils may provide higher market revenues. These farm management aspects are the drivers of the profitability of soil compaction renovation evaluated here.

Higher or lower expected crop prices partly cancel each other out when analysing the profitability of renovation investment: years of set-aside because of renovation imply lost market revenues during the first years of the renovation. The higher the expected future market prices, the greater are these losses. On the other hand, these losses are compensated for by the increased market revenues from production due to increased crop yields after renovation. Higher crop yields after renovation should outweigh the lost market revenues during the early years of renovation, over the modelled time span of 30 years.

3. Results

3.1. Land use in compacted parcels scenario

The decreased productivity of parcels 3 and 7 affects land allocation at the whole-farm level. The area of NMF is the maximum area allowed by the agri-environmental scheme, mostly allocated on field parcels 3 and 7 due to lower yield expectations (Table 3). If there were no soil compaction, the area of NMF would be lower and allocated mostly to the furthest parcels, instead of parcels 3 and 7 (Appendix Table A1). Malting barley is not suitable for compacted soil and therefore its area decreases in parcels 3 and 7 compared to the base scenario. Most of this area is taken by NMF and spring wheat cultivation.

Winter wheat is not produced at all in compacted parcels scenario. Minor changes occur in the areas of feed barley (decrease) and oilseed (increase). Almost all permitted NMF area is allocated to the compacted soils. This means that a farmer must also allocate land in a different way in other parcels. Production intensifies further now in parcels 8–10

Table 3
Parcel specific land allocation (average over 30 years) in the compacted parcels scenario (CP) and in the renovated soil scenario (RS) with base prices.

	SWheat		WWheat		FBarley		MBarley		Oats		Oilseed		Setaside		NMF	
	CP	RS	CP	RS	CP	RS	CP	RS	CP	RS	CP	RS	CP	RS	CP	RS
PARCEL 1	27%	23%	0%	0%	0%	0%	47%	47%	7%	10%	20%	20%	0%	0%	0%	0%
PARCEL 2	27%	23%	0%	0%	0%	0%	47%	47%	7%	3%	20%	27%	0%	0%	0%	0%
PARCEL 3	38%	13%	0%	0%	0%	0%	0%	43%	2%	5%	13%	17%	0%	10%	47%	12%
PARCEL 4	20%	20%	0%	0%	0%	0%	47%	47%	13%	8%	20%	22%	0%	0%	0%	3%
PARCEL 5	17%	17%	0%	0%	0%	0%	50%	47%	17%	13%	17%	13%	0%	0%	0%	10%
PARCEL 6	53%	47%	0%	3%	0%	0%	0%	0%	33%	40%	13%	10%	0%	0%	0%	0%
PARCEL 7	17%	13%	0%	0%	0%	0%	0%	30%	7%	15%	2%	13%	0%	10%	75%	18%
PARCEL 8	21%	13%	0%	0%	0%	0%	31%	30%	27%	20%	17%	17%	0%	0%	5%	20%
PARCEL 9	17%	10%	0%	0%	2%	7%	25%	20%	35%	23%	13%	13%	0%	0%	8%	27%
PARCEL 10	15%	0%	0%	0%	17%	25%	0%	3%	40%	25%	13%	7%	0%	0%	15%	40%
AVG.	25.1%	18.0%	0.0%	0.3%	1.8%	3.2%	24.6%	31.3%	18.7%	16.3%	14.8%	15.8%	0.0%	2.0%	15.0%	13.0%

where liming is increased and the area of crops increase as well. Fungicide treatment frequency varies from 0 to 74% depending on the crop (Table 3; Appendix Table A1).

Overall, the model results suggests that an optimizing farmer can find some ways to avoid economic losses due to soil compaction, and the overall loss in gross margin is as low as 6.7% (base prices) compared to the scenario where there is no soil compaction, despite 30% yield losses in field parcels 3 and 7, which represent 20% of the total area of the farm (Appendix Table A1).

Higher crop prices would increase the area of high-profit crops whereas lower crop prices would increase the area of set-aside and feed barley.

3.2. Land use in renovation scenario

When compacted soils in field parcels 3 and 7 are renovated, their productivity increases back to average levels at year 4. Now, from year 4, set-aside and NMF are allocated mostly to the farthest away field parcels, as in the base scenario (Table 3; Appendix Table A1). However the crop rotation requirement in the renovation scenario maintains some of the set-aside and NMF in field parcels 3 and 7. High-profit crops (malting barley, spring wheat and oilseed rape) are now allocated to those parcels. However, since the high-profit crops cannot be cultivated every year in parcels 3 and 7 due to the crop rotation constraint it is also not profitable to intensify production by liming those field parcels, as in the base scenario. Whereas NMF was allocated to parcels 3, 7 and 10 in the compaction scenario with base prices, NMF is now allocated to parcels 8–10 due to high logistics costs. Land allocation is very similar in the compacted parcels scenario and the renovation scenario in parcels 1–2 and 4–6. The main differences thus occur between compacted parcels and furthest parcels (Table 6).

As in the case of the compacted parcels scenario, higher crop prices would increase the area of high-profit crops whereas lower crop prices would increase the area of set-aside and feed barley.

3.3. Differences in input use, crop yields, gross margins, total production and GHG emissions in the scenarios

3.3.1. Base price scenarios

There is no difference in fertilisation per crop between the compacted parcels scenario and the renovation scenario. The average pH calculated over all field parcels in the compacted parcels scenario with base prices is 0.07 higher compared to the average soil pH in the renovation scenario (Table 4). Hence it is profitable to increase pH in other field parcels and allocate NMF to compacted parcels. In the compacted parcels scenario, liming is low in compacted parcels 3 and 7 and in the furthermost parcel 10 whereas in case of the renovation scenario liming is also low in parcels 8 and 9.

These results are explained by the assumption that liming is made by contractor which means that logistics costs do not play a role in the decision whether to spread lime on individual field parcels or not. Although yield potential is higher in renovated parcels, crop rotation requirements discourage farmer from using liming. In the compaction parcel scenario a farmer is forced to use almost all the permitted NMF area for compacted parcels and shift some intensive production to further parcels and therefore also to spread lime on these parcels. In the renovation scenario the NMF area is allocated to the furthest parcels due to logistics costs.

Fungicide treatment frequencies are almost similar in both scenarios. Fungicide use is absent in the compacted parcels but is more common in other parcels.

The NPV of annual average farm level gross margins is 2.7% higher and overall production is 3.0% higher in the renovation scenario than in the compacted parcels scenario (Table 4). GHG emissions decrease by 0.4%, and emissions per unit produced decrease by 3.3% if a farmer chooses renovation instead accepting compacted soils on field parcels 3 and 7.

Average yields of the whole farm increase generally by 2.1–8.2% if choosing the renovation scenario instead of the compacted parcels scenario. Average yields of malting barley decrease by 0.6% (Table 4). In the compacted parcels scenario, production is shifted from compacted parcels to non-compacted parcels that are further away from the farm centre, and NMF is allocated to compacted parcels. This allocation decreases the average yield losses caused by compaction.

3.3.2. High price scenarios

When crop prices increase from the baseline price level, the cumulative discounted gross margin increases in the renovation scenario slightly more than in the compacted parcels scenario. This is understandable since renovated field parcels provide increased potential for market revenues.

Increased crop prices encourage farmers to increase malting barley and spring wheat areas and increase the use of inputs. In the compacted parcels scenario, the low yield potential from the compacted parcels restricts farmers to exploiting all the gains provided by higher market prices. Thus the gains from renovation increase as the output prices increase. Liming is now, under high crop prices, more intense in the renovation scenario than in the case of the compacted parcels scenario. This difference is caused by the lower yield potential from the compacted parcels. In the renovation scenario, output prices are now high enough to make liming profitable on renovated parcels despite the crop rotation requirements, unlike in the base price scenario.

When crop prices are high, production is intense also in the furthest parcels in both compacted parcels and renovation scenarios. This can be seen in low set-aside areas and high average pH value of soils (Table 4). Liming differs considerably between the scenarios only on parcels 3 and 7. In the compacted parcels scenario lime is not spread on parcels 3 and 7 whereas in the renovation scenario liming in those parcels is almost as

Table 4
Whole-farm level comparison of the simulated objective value of the model, average certainty-equivalent (CE) gross margin per ha, average pH values of soils, GHG emissions, total production as feed energy, GHG emissions per feed unit produced and average yields for compacted parcels (CP) and renovation (RS) scenarios with different crop prices.

Average crop prices	CP	RS	Difference
Value (€) of objective function over 30 years	41,460	42,561	2.7%
Average CE gross margin €/ha/year	138	142	2.7%
Average pH	6.10	6.03	−1.2%
Average pH, parcel 3	5.73	5.70	−0.4%
Average pH, parcel 7	5.77	5.71	−1.0%
Average GHG emissions tons CO2 eq/ha	3.32	3.31	−0.4%
Total production, GJ/ha	31,301	32,226	3.0%
GHG emissions tons CO2 / GJ	0.106	0.103	−3.3%
Average yields			
Spring wheat	3214	3478	8.2%
Winter wheat	NA	4099	NA
Feed barley	3596	3673	2.1%
Malting barley	3703	3682	−0.6%
Oats	3515	3608	2.7%
Oilseed rape	1557	1602	2.9%
Percentage of fungicide treatment area ([a]SW, WW, FB, MB)	44%	51%	

High crop prices	CP	RS	Difference
Value (€) of objective function over 30 years	54,098	56,590	4.6%
Average CE gross margin €/ha/year	180	189	4.6%
Average pH	6.28	6.42	2.3%
Average pH, parcel 3	5.71	6.46	13.1%
Average pH, parcel 7	5.75	6.46	12.2%
Average GHG emissions tons CO2 eq/ha	3.52	3.59	1.9%
Total production, GJ/ha	34,554	38,123	10.5%
GHG emissions tons CO2/GJ	0.102	0.094	−7.7%
Average yields			
Spring wheat	3454	3868	12.0%
Winter wheat	4177	4133	−1.1%
Feed barley	NA	NA	NA
Malting barley	3874	3912	1.0%
Oats	3741	3845	2.8%
Oilseed rape	1689	1782	5.5%
Percentage of fungicide treatment area ([a]SW, WW, FB, MB)	89%	100%	

Low crop prices	CP	RS	Difference
Value(€) of objective function over 30 years	30,446	31,228	2.6%
Average CE gross margin €/ha/year	102	104	2.6%
Average pH	5.69	5.68	−0.1%
Average pH, parcel 3	5.75	5.72	−0.5%
Average pH, parcel 7	5.79	5.73	−1.0%
Average GHG emissions tons CO2 eq/ha	3.07	3.12	1.8%
Total production, GJ/ha	25,323	27,683	9.3%
GHG emissions tons CO2 / GJ	0.121	0.113	−6.9%
Average yields			
Spring wheat	2852	3030	6.2%
Winter wheat	NA	NA	NA
Feed barley	3525	3585	1.7%
Malting barley	3170	3211	1.3%
Oats	3350	3408	1.7%
Oilseed rape	1262	1349	6.9%
Percentage of fungicide treatment area ([a]SW, WW, FB, MB)	0%		

[a] SW = spring wheat, WW = winter wheat, FB = feed barley, MB = malting barley.

intense as in the other parcels. Thus intensity of production is almost similar in both scenarios if we do not take into account parcels 3 and 7. Crop yields are 1.0–12.0% higher in the renovation scenario. An exception is the average yield of winter wheat which is 1.1% lower in the renovation scenario than in the compacted parcels scenario (Table 4). High crop prices also trigger full use of fungicides. Fungicides are used always in the renovation scenario and in the compaction scenario in other parcels than 3 and 7.

3.3.3. Low price scenarios

When prices decrease 20% compared to the base prices, production quantity is reduced in both compacted parcels and renovation scenarios. The use of inputs decreases and the area under set-aside increases due to low prices. Management practices are similar in both scenarios (compacted parcels and renovation); there is little liming and it is not profitable to use fungicides if low crop prices are realized (Table 4). Difference in average yields and in other main results comes from the changed yield potential, due to soil renovation, in parcels 3 and 7. Farmers allocate more land to set-asides in both scenarios if low crop prices are realized. Therefore the difference in average whole farm gross margins between the compacted parcels scenario and the renovation scenario is lower than in other price scenarios.

3.4. Renovation net present values and payback times

With baseline prices, the accumulated net present value of future income of the renovation scenario exceeds the net present value of future income of the compacted parcels scenario in the eighth year (Table 5). NPV calculated for the whole farm is only 1102 € (2.7%) higher (taking into account the investment cost and implicit lost gross margins due to the crop rotation constraints for field parcels 3 and 7) over the 30-year time period.

Renovation pays off much better when crop prices are 20% higher during the 30-year long time period: Economic gains reach almost 2492 € (4.6%) and payback time is eleven years. It is noticeable that payback time is longer than in the base price scenario. This can be explained by liming decisions, and by the fact that high prices imply both higher income losses in the first periods, and then higher gains the later periods, if parcels are renovated. When output prices are high, farmers intensify production. Liming can be considered as a long-term investment which gains higher income in the future. However increased liming with increased costs in the first years after renovation may delay the pay-back of the renovation investment, even if the NPV over 30 years is much higher than in the case of no renovation. If crop prices are 20% lower compared to the baseline prices, the payback time of the renovation is eleven years and the difference in the net present value of future income between compacted parcels and renovation scenarios is (782 €) 2.6% which is slightly lower than in the base price scenario.

We calculated the results of Table 5 also assuming −10% and − 20% crop yield losses at compacted parcels, assuming baseline prices (average crop prices 2000–2014). The results suggest that when compaction is not severe, the gain in NPV achieved by renovating soil compaction is small and payback time is long. When yield losses are only 10% the NPV of renovation scenario does not exceed the NPV of compaction scenario in our 30-year time span.

3.5. NPV, payback times and farm management under different discount rates

Although our main results are calculated assuming a discount rate of 6% we made a simple sensitivity analysis at different discount rates 1–10% (Table 7).

We find that NPV values decrease consistently when the discount rate is increased. The difference between the NPV between compacted parcel and renovation scenarios decrease as the discount rate increases. This is understandable since future revenues decrease in their discounted value and investing in soil renovation becomes relatively less profitable. Still the soil renovation is profitable, that is NPV with renovation is higher than the NPV without renovation, even at 10% discount rate.

What is interesting, however, that the payback time, the year when

Table 5
Net present value of future certainty-equivalent income (€) in the renovation scenario (RS) and the compacted parcels (CP) scenario, the difference between scenarios and per renovated field parcel, also calculated per year, and per renovated field parcel per year, and the payback time of the investment (years). BP = baseline prices 2000–2014. Source: Author's simulations using DEMCROP farm level model. Discount rate = 6%.

Price scenario	NPV (€) for 30 years		Difference (€) RS/CP	Difference, €/ renovated parcel/ year	Payback time, years
	CP	RS			
−20%	30,451 (−26.6%)	31,233 (−26.6%)	782 (2.6%)	13	11
BP	41,465	42,566	1102 (2.7%)	18	8
+20%	54,103 (30.5%)	56,596 (33.0%)	2492 (4.6%)	42	11

Table 6
Net present value of future certainty-equivalent income (€) in the renovation scenario (RS) and the compacted parcels (CP) scenario assuming −10%, −20% and − 30% crop yield reduction, the difference between scenarios and per renovated field parcel, also calculated per year, and per renovated field parcel per year, and the payback time of the investment (years). Baseline prices 2000–2014 are assumed. Source: Author's simulations using DEMCROP farm level model. Discount rate = 6%.

Assumed crop yield loss at compacted parcels	NPV (€) for 30 years		Difference (€) RS/CP	Difference, €/ renovated parcel/ year	Payback time, years
	CP	RS			
−10%	42,797	42,566	−231 (−0.5%)	−4	> 30
−20%	42,007	42,566	560 (1.3%)	9	13
−30%	41,465	42,566	1102 (2.7%)	18	8

a farmer gets the money back from the soil-renovation investment, including the condition that deep-rooted crops are grown on compacted parcels 3 and 7 to avoid further compaction, varies when discount rate is changed. First, at low discount rates 1–5% the payback time is stable, 10–12 years, but decreases to just 7 years when the discount rate is increased up to 6%, and then increases again to 10–13 years when increasing the discount rate up to 10%.These results are explained by the liming intensity, with dynamic impacts on soil pH and crop yield levels, as explained in Section 3.4.

4. Discussion

Renovation of compacted soil takes time and requires maintenance and changes in crop rotations at a farm, for example growing deep-rooted crops regularly on field parcels prone to soil compaction. All this, including investment cost and low market revenues at the first years from renovated field parcels, leads to long payback times, most likely 8–12 as suggested by the results when yield reductions due to compaction are assumed −30%, even when considering the implied changes in management and profitability at the whole-farm level. If farmers face soil compaction problems, they can find ways to mitigate economic losses due to low crop yields in those parcels. Most likely, set-asides or crops with low prices are allocated to the compacted parcels and not that much in other field parcels. Consequently, the difference in profitability between the renovation option and continuing with compacted soils decreases and this may lead to longer payback times for soil-renovation investments.

Soil compaction may imply allocatisng more cereals production and cereals monocultures on field parcels that are not currently compacted. This may imply spring cereals monocultures which may have a relatively higher risk for soil compaction compared to crop rotations with break crops. We assumed such risk is low, however, which means that the field parcels not currently compacted are not prone to compaction. This assumption may not be true in all cases. Even though the differences in the land use of non-compacted soils are not very significant between the baseline (Appendix Table A2) and compacted parcels and renovation scenarios (Table 3), the results of this study nevertheless show that soil renovation implies more production on parcels 3 and 7, and slightly decreasing cereals production on all other parcels, compared to the compacted parcels scenario. Hence if soil compaction is more likely in the production of spring cereals then soil renovation may decrease the risk of soil compaction on non-compacted parcels since part of the cereals production of a farm shifts to the renovated field parcels.

Existing agri-environmental payments paid for non-harvested crops suitable for soil renovation (e.g. subsidies for green manure, accounted for in this study) incentivise soil renovations since they alleviate the loss of market revenues during the first years of renovation. Therefore it

Table 7
Net present values of certainty equivalent gross margins calculated in the case of compacted parcels (CP) and renovation (RS) scenarios with different discount rates.

Discount rate	Payback time, years	CP	RS	CP	RS	Difference in NPV	Difference
		Avg. pH	Avg. pH	NPV €	NPV €		
0%	10	6.48	6.66	92,862	98,406	5544	6.0%
1%	10	6.44	6.62	79,267	83,998	4731	6.0%
2%	10	6.41	6.56	68,421	72,051	3630	5.3%
3%	12	6.36	6.51	59,708	62,529	2820	4.7%
4%	10	6.31	6.38	52,438	54,641	2203	4.2%
5%	11	6.25	6.31	46,480	48,218	1738	3.7%
6%	8	6.10	6.03	41,465	42,566	1102	2.7%
7%	10	5.90	5.85	37,150	38,177	1027	2.8%
8%	11	5.68	5.68	33,494	34,423	929	2.8%
9%	12	5.68	5.68	30,779	31,449	670	2.2%
10%	14	5.66	5.66	28,422	28,888	466	1.6%

is important that such indirect incentives for soil improvements are maintained if increased productivity and effective use of agricultural resources are essential means for developing sustainability of agriculture.

Renovation increases the average gross margin per hectare by 18 €/ha/year in a 30-year time span with 2000–2014 average crop prices when yield decreases due to compaction are assumed to be −30%. This gain in the average gross margin is about 28% lower compared to the calculations reported by Chamen et al. (2015) where 25 €/ha average increase in gross margin was estimated for subsoiling in the UK. It is worth noting that the calculations of Chamen et al. (2015) were based on data where the yield loss due to compaction varied around 15–30% whereas in this case the assumed yield loss is 30%. The estimations of Chamen et al. (2015) were based on a static situation, in the UK context. We took into account dynamic whole-farm management implications of soil renovation using dynamic optimisation. Jin et al. (2007) estimated considerably higher net profits due to subsoiling compared to our study, but subsoiling was incorporated there to other farming practices which might also loosen the soil. However we could not find many studies on the profitability of soil renovation, with a set up and assumptions (compacted soils are 20% of the land area of a cereals farm and 30% yield loss at the compacted field parcels) close to our case in south-west Finland, in the literature. Thus our results cannot be directly compared to other studies. When yield losses due to compaction are assumed to be lower than −30% profitability of soil renovation is low and payback times are long.

5. Conclusions

We analysed the profitability of compacted soil renovation using dynamic optimisation with multiple input use responses. We assumed soil compaction at 20% of the field plots, with a 30% yield loss, at a typical cereals producing farm in south-west Finland. Our results, calculated assuming current policy environment and 2000–2014 average prices, show that soil renovation would result in about a 18 €/ha/year increase in profit at the whole-farm level over a 30-year time span from the renovated parcel. Our analysis took fully into consideration the following assumption: Crop yield losses could be avoided with subsoiling and altered crop rotation, including deep-rooted crops at least 3 times every decade. The results suggest that soil compaction renovation will most likely pay back, but the payback time can be long due to low profitability of crop production on average farms. This may demotivate some farmers from making renovation investments. Our analysis assumed 6% discount rate but also shows that high discount rate (e.g. 10%) will result in small but still positive economic gains from soil renovation. However, soil renovation cannot be recommended as a solution to acute economic problems at a farm but rather as a long-term investment that provides economic benefits if the increased production potential is rationally utilized after the soil renovation.

It is often the case that some individual field parcels are prone to soil compaction, or compacted already. In our case, where two field parcels out of ten were compacted and renovated, the farm level net present value is 2.7% higher and overall production 3.0% higher in the renovation scenario than in the compacted parcels scenario, at average 2000–2014 prices. The net present value of soil renovation could be 4.6% higher if 20% higher crop prices were realized. Decrease in relative output prices would slightly decrease the profitability of soil renovation. However, soil renovation under our assumptions is still positive if 20% lower crop prices compared to the 2000–2014 average prices are realized. Payback time of soil renovation, under our assumptions, is most likely 8–12 years. Thus soil renovation cannot be considered highly profitable but it could be considered a low-regret decision at least on farms which aim for high productivity and plan to grow high valued crops. On the other hand, our results suggest that soil renovation may not increase production at a farm very significantly if all land resources are not fully used initially but some land is allocated for set-aside because of agri-environmental incentives, as in our case. Still soil renovation is worth more than it costs if the yield losses caused by compaction are severe, and if soil renovation implies a significantly increased production potential and increased possibilities for production rationalisation, taking into account logistic costs. Soil renovation investment may not be worth more than it costs if soil compaction is not severe and resulting crop yield losses are minor. This is likely if the renovation method is expensive, e.g. subsoiling accompanied with green manuring during the first 3 years after subsoiling, and with crop rotation requirements where deep-rooted crops or grasslands must be cultivated regularly. Our results suggest very low increase in average gross margins and long payback times if crop yield losses due to soil compaction are 20% or lower.

There is a need for suitable tools for analysing this type of economic decision problem at the farm level, not least due to sustainable intensification and other strategies aiming to improve agricultural productivity and the environmental effects of agriculture. This study shows that dynamic optimisation with multiple responses (DEMCROP model in our case) clearly catches the adjustment rategies with needed crop rotation changes at a whole-farm level in different scenarios and shows economically rational production adjustments due to soil compaction or soil renovation under current agricultural and agri-environmental policy. Our results show that rational production management matters in the case of soil renovation, to be able to reap the benefits of improved crop yield levels. The relatively long payback times, on the other hand, is a message to policy makers: possible environmental and societal benefits of soil renovation may not be easily realized on farms if the profitability of production is low, or if it is difficult to find compensation for foregone market revenue due to soil renovation. Agri-environmental payments for suitable renovation crops, such as green manure, thus provide some indirect incentive for soil renovation. Further studies are needed to estimate the environmental effects of soil renovation. The effects of different farming practices combined with subsoiling could also be worth studying.

Declaration of Competing Interest

The authors (Mr. Tuomo Purola & Professor Heikki Lehtonen) declare no conflict of interest.

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Appendix A. Base scenario validation

Base scenario assumes average crop prices 2000–2014, and assumes no soil compaction. We analyse the base scenario outcomes of the model for two main reasons: (1) the results of the base scenario, which show how the farm is managed without yield losses, are an important point of comparison for the compaction and renovation scenarios; (2) The summarised base scenario results below also show the effects of higher and lower than expected price levels of crop products on land use, input use, crop yields and farm gross margin.

Simulated average yields are close to the observed yields in the region. The difference between simulated and observed yields varies from oilseed rape's -6.8% to malting barley's -2.6% (Table A2).

The average simulated soil pH at the farm is 6.10 (Table A2) which is exactly the average pH at the study area (6.1 according to Myyrä et al., 2005). The soil pH is the highest in parcels which are close to the farm centre and the lowest in parcels which are further away from the farm centre. Fungicide treatments are given to about 45% of the cultivated area of spring wheat, winter wheat and feed and malting barley in the simulation results (Table A2). This is consistent with the study of Mäenpää (2010) which reported fungicide use at 50% of farms.

The average farm level gross margin is 148 €/ha per year, calculated over a 30-year time period. Greenhouse gas emissions are 3.34 ton CO_2 eq. per ha per year. Total production as feed energy units are 33 335 GJ /ha/year. Emissions per unit produced are 0.100 (Table A2).

Table A1
Land use shares of different crops at each parcel (1 − 10) and on average on the whole farm, in the base scenario (no soil compaction) assuming average (2000–2014) prices. SWheat = spring wheat; WWheat = winter wheat; FBarley = feed barley; Mbarley = malting barley; Oilseed = oilseed rape; NMF = nature management field (set-aside); Setaside = Other set-aside, not eligible for NMF payments from agri-environmental scheme.

	SWheat	WWheat	FBarley	MBarley	Oats	Oilseed	Setaside	NMF
Parcel 1	27%	0%	0%	47%	7%	18%	0%	2%
Parcel 2	30%	0%	0%	47%	3%	20%	0%	0%
Parcel 3	20%	0%	0%	50%	13%	17%	0%	0%
Parcel 4	22%	0%	0%	47%	10%	18%	0%	3%
Parcel 5	20%	0%	0%	47%	8%	17%	0%	8%
Parcel 6	43%	7%	0%	0%	37%	13%	0%	0%
Parcel 7	5%	0%	0%	45%	20%	13%	0%	17%
Parcel 8	15%	0%	0%	27%	20%	12%	0%	27%
Parcel 9	12%	0%	0%	20%	23%	8%	0%	37%
Parcel 10	5%	0%	22%	0%	27%	5%	0%	42%
Farm level average	19.8%	0.7%	2.2%	32.8%	16.9%	14.2%	0.0%	13.5%

Table A2
Farm level results of optimised management in the base scenario, under different crop prices over a 30-year time period. Discount rate = 6%.

	Low prices	Base prices	High prices
NPV (€) of objective function over 30 years	32,472	44,453	58,740
NPV (€) of risk over 30 years (% of objective)	5.20€ (0.016%)	5.50 (0.012%)	6.00 (0.010%)
Certainty-equivalent gross margin, €/ha	108	148	196
Average pH	5.68	6.10	6.43
Average GHG emissions tons CO2 equiv./ha	3.13	3.34	3.63
Total production, GJ/ha	27,977	33,335	38,930
GHG emissions tons CO2 / GJ	0.112	0.100	0.093
Fungicide treatment frequency	0%	58%	100%
Average yields (kg/ha)			
Spring wheat	3007 (−13.9%)	3492 (3720)	3832(+9.7%)
Winter wheat	NA	3733 (3986)	4305 (+15.3%)
Feed barley	3610 (−1.9%)	3681 (3814)	NA
Malting barley	3228(−13.1%)	3715 (3815)	3901 (+5.0%)
Oats	3439 (−5.5%)	3640 (3807)	3852 (+5.8%)
Oilseed rape	1302 (−19.5%)	1616 (1734)	1759 (+8.8%)

Table A3
A covariance matrix of gross margins of the crops and set-asides based on gross margins in Varsinais-Suomi region, Finland 2000–2015. SWheat = spring wheat; WWheat = winter wheat; FBarley = feed barley; Mbarley = malting barley; Oilseed = oilseed rape; NMF = nature management field (set-aside); Setaside = Other set-aside, not eligible for NMF payments from agri-environmental scheme.

	Swheat	WWheat	FBarley	Mbarley	Oats	Oilseed	Setaside	NMF
Swheat	17,141	18,817	14,459	19,224	14,644	16,543	2757	5623
WWheat	18,817	27,241	15,441	20,782	17,497	18,351	2873	6285
FBarley	14,459	15,441	13,632	17,409	13,496	13,433	2467	4836
Mbarley	19,224	20,782	17,409	25,607	16,775	20,136	3961	7473
Oats	14,644	17,497	13,496	16,775	14,923	13,614	2402	4776
Oilseed	16,543	18,351	13,433	20,136	13,614	21,408	4967	9006
Setaside	2757	2873	2467	3961	2402	4967	2168	3384
NMF	5623	6285	4836	7473	4776	9006	3384	5517

References

Alakukku, L., 2012. Combatting soil degradation: soil compaction. In: Jakobsson, C. (Ed.), Ecosystem Health and Sustainable Agciculture 1: Sustainable Agriculture, pp. 217–221.
Alakukku, L., Weisskopf, P., Chamen, W.C.T., Tijink, F.G.J., Van Der Linden, J.P., Pires, S., Sommer, C., Spoor, G., 2003. Prevention strategies for field traffic-induced subsoil compaction: a review part 1. Machine/soil interactions. Soil Tillage Res. 73, 145–160. https://doi.org/10.1016/S0167-1987(03)00107-7.
Anderson, J.R., Dillon, J.L., 1992. Risk analysis in dryland farming systems. In: Rome Food Agric. Organ. United Nations, pp. 1992.
Berntsen, J., Petersen, B.M., Jacobsen, B.H., Olesen, J.E., Hutchings, N.J., 2003. Evaluating nitrogen taxation scenarios using the dynamic whole farm simulation

model FASSET. Agric. Syst. 76, 817–839. https://doi.org/10.1016/S0308-521X(02)00111-7.

Chamen, W.C.T., Moxey, A.P., Towers, W., Balana, B., Hallett, P.D., 2015. Mitigating arable soil compaction: a review and analysis of available cost and benefit data. Soil Tillage Res. 146, 10–25. https://doi.org/10.1016/j.still.2014.09.011.

Chardon, X., Rigolot, C., Baratte, C., Espagnol, S., Raison, C., Martin-Clouaire, R., Rellier, J.P., Le Gall, A., Dourmad, J.Y., Piquemal, B., Leterme, P., Paillat, J.M., Delaby, L., Garcia, F., Peyraud, J.L., Poupa, J.C., Morvan, T., Faverdin, P., 2012. MELODIE: a whole-farm model to study the dynamics of nutrients in dairy and pig farms with crops. Animal 6, 1711–1721. https://doi.org/10.1017/S1751731112000687.

Dueri, S., Calanca, P.L., Fuhrer, J., 2007. Climate change affects farm nitrogen loss - a Swiss case study with a dynamic farm model. Agric. Syst. 93, 191–214. https://doi.org/10.1016/j.agsy.2006.05.005.

Farmit, 2019. Viljakasvien kalkitus [WWW Document]. URL. https://www.farmit.net/kasvinviljely/kalkitus-ja-maanparannus/kasvien-ph-vaatimukset/viljakasvit accessed 4.11.19.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, L., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327 (80), 812–818.

Grevers, M.C.J., Taylor, J., 2013. The economic feasibility of subsoiling Solonetzic soils in Saskatchewan. J. Prod. Agric. 8, 557–561.

Håkansson, I., Henriksson, L., Gustafsson, L., 1985. Experiments on reduced compaction of heavy clay soils and sandy soils in Sweden. J. Terramechanics 22.

Håkansson, I., Voorhees, W.B., Elonen, P., Raghavan, G.S.V., Lowery, B., Van Wijk, A.L.M., Rasmussen, K., Riley, H., 1987. Effect of high axle-load traffic on subsoil compaction and crop yield in humid regions with annual freezing. Soil Tillage Res. 10, 259–268. https://doi.org/10.1016/0167-1987(87)90032-8.

Hamidov, A., Helming, K., Bellocchi, G., Bojar, W., Dalgaard, T., Ghaley, B.B., Hoffmann, C., Holman, I., Holzkämper, A., Krzeminska, D., Kvaernø, S.H., Lehtonen, H., Niedrist, G., Øygarden, L., Reidsma, P., Roggero, P.P., Rusu, T., Santos, C., Seddaiu, G., Skarbøvik, E., Ventrella, D., Żarski, J., Schönhart, M., 2018. Impacts of climate change adaptation options on soil functions: a review of European case studies. L. Degrad. Dev. 1–12. https://doi.org/10.1002/ldr.3006.

Hoefer, G., Hartge, K.H., 2010. Subsoil compaction: Cause, impact, detection, and prevention. In: Dedousis, A., Bartzanas, T. (Eds.), Soil Engineering. SOILBIOL. 20. Springer, Berlin, Heidelberg, pp. 121–145. https://doi.org/10.1007/978-3-642-03681-1_9.

Höglind, M., Thorsen, S.M., Semenov, M.A., 2013. Assessing uncertainties in impact of climate change on grass production in Northern Europe using ensembles of global climate models. Agric. For. Meteorol. 170, 103–113. https://doi.org/10.1016/j.agrformet.2012.02.010.

Horn, R., Domialb, H., Slowihka-Jurkiewiczb, A., Van Ouwerkerkct, C., 1995. Soil compaction processes and their effects on the structure of arable soils and the environment. Elsevier Sci. B.V.Soil Tillage Res. 35, 23–36. https://doi.org/10.1016/0167-1987(95)00479-C.

Jin, H., Hongwen, L., Xiaoyan, W., Mchugh, A.D., Wenying, L., 2007. The adoption of annual subsoiling as conservation tillage in dryland maize and wheat cultivation in northern China. 94, 493–502. https://doi.org/10.1016/j.still.2006.10.005.

Kocherlakota, N.R., 1996. The equity premium : it' s still a puzzle. J. Econ. Lit. XXXIV, 42–71.

Lehtonen, H., 2001. Principles, Structure and Application of Dynamic Regional Sector Model of Finnish Agriculture. Agrifood Research Finland, Economic Research (MTTL).

Lehtonen, H., Niemi, J., 2018. Effects of reducing EU agricultural support payments on production and farm income in Finland. Agric. Food Sci. 27, 124–137 (https://doi.org/https://doi.org/10.23986/afsci.67673).

Lehtonen, H., Liu, X., Purola, T., 2014. Endogenising yield development through management and crop rotation decisions in dynamic farm level modeling. In: In: 24. Jahrestagung Der Österreichischen Gesellschaft Für Agrarökonomie, Universität Für Bodenkultur Wien 25.-26. September 2014. Tagungsband. 2014. pp. 13–14.

Lehtonen, H., Liu, X., Purola, T., 2016. Balancing climate change mitigation and adaptation with the socio-economic goals of farms in Northern Europe. In: Climate Change Adaptation and Food Supply Chain Management, https://doi.org/10.4324/9781315757728.

Lemola, R., Uusitalo, R., Hyväluoma, J., Sarvi, M., 2018. Suomen peltojen maalajit, multavuus ja fosforipitoisuus. Helsinki.

Liu, X., Lehtonen, H., Purola, T., Pavlova, Y., Rötter, R., Palosuo, T., 2016. Dynamic economic modelling of crop rotations with farm management practices under future pest pressure. Agric. Syst. 144. https://doi.org/10.1016/j.agsy.2015.12.003.

Luke, 2019. Economydoctor. In: Natural Resources Institute Finland. FADN Standard Results. Field crops Southern Finland.

Mäenpää, A., 2010. Plant Disease Forecasting Model, Needs and Usefulness. HAMK university of applied sciences.

McAfee, M., Lindström, J., Johansson, W., 1989. Effects of pre sowing compaction on soil physical properties soil atmosphere and growth of oats on a clay soil. J. Soil Sci. 40, 707–718.

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. Nature 490, 254–257. https://doi.org/10.1038/nature11420.

Myyrä, S., Ketoja, E., Yli-Halla, M., Pietola, K., 2005. Land improvements under land tenure insecurity: the case of pH and phosphate in Finland. Land Econ. 81, 557–569. https://doi.org/10.3368/le.81.4.557.

Official Farm Statistics (OFS), 2018. Crop Yield Statistics, Utilized Agricultural Area [Web Publication], 2018 [WWW Document]. URL. http://stat.luke.fi/en/crop-production-statistics.

OSF, 2014. Official Statistics of Finland: Statistics on the Finances of Agricultural and Forestry Enterprises [WWW Document]. URL. https://tilastokeskus.fi/til/mmtal/index_en.html.

Palosuo, T., Rötter, R.P., Salo, T., Peltonen-Sainio, P., Tao, F., Lehtonen, H., 2015. Effects of climate and historical adaptation measures on barley yield trends in Finland. Clim. Res. 65, 221–236. https://doi.org/10.3354/cr01317.

Peltonen-Sainio, P., Jauhiainen, L., Hannukkala, A., 2007. Declining rapeseed yields in Finland: how, why and what next? J. Agric. Sci. 145, 587–598. https://doi.org/10.1017/S0021859607007381.

Peltonen-Sainio, P., Salo, T., Jauhiainen, L., Lehtonen, H., Sievil??inen, E., 2015. Static yields and quality issues: is the Agri-environment program the primary driver? Ambio 44, 544–556. https://doi.org/10.1007/s13280-015-0637-9.

Peltonen-Sainio, P., Venäläinen, A., Mäkelä, H.M., Pirinen, P., Laapas, M., Jauhiainen, L., Kaseva, J., Ojanen, H., Korhonen, P., Huusela-Veistola, E., Jalli, M., Hakala, K., Kaukoranta, T., Virkajärvi, P., 2016. Harmfulness of weather events and the adaptive capacity of farmers at high latitudes of Europe. Clim. Res. 67, 221–240. https://doi.org/10.3354/cr01378.

Petsakos, A., Rozakis, S., 2015. Calibration of agricultural risk programming models. Eur. J. Oper. Res. 242, 536–545. https://doi.org/10.1016/j.ejor.2014.10.018.

Pirinen, P., Simola, H., Aalto, J., Kaukoranta, Juho-Pekka Karlsson, P., Ruuhela, R., 2012. Tilastoja Suomen ilmastosta 1981–2010 (Climatological statistics of Finland 1981–2010). Ilmatieteen laitoksen raportteja 2012:1.

Purola, T., 2013. audinkestävien ja tautialttiiden ohralajikkeiden taloudellinen vertailu. University of Helsinki.

Purola, T., Lehtonen, H., Liu, X., Tao, F., Palosuo, T., 2018. Production of cereals in northern marginal areas: an integrated assessment of climate change impacts at the farm level. Agric. Syst. 162. https://doi.org/10.1016/j.agsy.2018.01.018.

Raskin, R., Cochran, M.J., 1986. Interpretations and transformations of scale for the Pratt-arrow absolute risk aversion coefficient : implications for generalized stochastic dominance. West. J. Agric. Econ. 11, 204–210.

Robison, L.J., Barry, P.J., 1987. Competitive firm's Response to Risk. New York.

Rötter, R.P., Höhn, J., Trnka, M., Fronzek, S., Carter, T.R., Kahiluoto, H., 2013. Modelling shifts in agroclimate and crop cultivar response under climate change. Ecol. Evol. 3, 4197–4214. https://doi.org/10.1002/ece3.782.

Ruixuan, C., Carpentier, A., Gohin, A., 2011. Measuring farmers' risk aversion: the unknown properties of the value function. EAAE, pp. 1–13.

Ruosteenoja, K., Räisänen, J., Pirinen, P., 2011. Projected changes in thermal seasons and the growing season in Finland. Int. J. Climatol. 31, 1473–1487. https://doi.org/10.1002/joc.2171.

Soanea, B.D., van Ouwerkerk, C., 1995. Implications of soil compaction in crop production for the quality of the environment. Soil Tillage Res. 35, 5–22.

Spoor, G., Tijink, F.G.J., Weisskopf, P., 2003. Subsoil compaction: risk, avoidance, identification and alleviation. Soil Tillage Res. 73, 175–182. https://doi.org/10.1016/S0167-1987(03)00109-0.

Tike, 2012. Use of Agricultural Land 2011. Official agricultural statistics [WWW Document]. URL. stat.luke.fi accessed 6.25.18.

Tike, 2014. Use of Agricultural Land 2013. Official agricultural statistics [WWW Document]. URL. stat.luke.fi accessed 6.25.18.

Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. 108, 20260–20264. https://doi.org/10.1073/pnas.1116437108.

Tracy, S.R., Black, C.R., Roberts, J.A., Mooney, S.J., 2011. Soil compaction: a review of past and present techniques for investigating effects on root growth. J. Sci. Food Agric. 91, 1528–1537. https://doi.org/10.1002/jsfa.4424.

Tulevaisuus, M., 2015. Maan tiivistyminen voi leikata suuren osan viljasadosta. Maaseudun Tulev. 1.

Van Den Akker, J.J.H., Arvidsson, J., Horn, R., 2003. Introduction to the special issue on experiences with the impact and prevention of subsoil compaction in the European Union. Soil Tillage Res. 73, 1–8. https://doi.org/10.1016/S0167-1987(03)00094-1.

Vogeler, I., Beukes, P., Burggraaf, V., 2013. Evaluation of mitigation strategies for nitrate leaching on pasture-based dairy systems. Agric. Syst. 115, 21–28. https://doi.org/10.1016/j.agsy.2012.09.012.

Vuorio, H., Soini, K., Ikonen, A., 2006. Kenestä erikoiskasviviljelijäksi? Erikoiskasviviljelyn omaksujatyypit ja omaksumisen taustalla vaikuttavat tekijät. Paper presented in "Maataloustieteen päivät", Helsinki, January 2006.

VYR, 2014. MALLASOHRAN VILJELYOPAS [WWW Document]. URL. http://vikingmalt.fi/wp-content/uploads/2015/08/mallasohraopas_printtiversio_web_140505.pdf.