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On the relationships between the size of agricultural machinery, soil quality and net revenues for farmers and society

Nargish Parvin [a,b], Elsa Coucheney [a], Ing-Marie Gren [c], Hans Andersson [c], Katarina Elofsson [c,d,e], Nicholas Jarvis [a,1], Thomas Keller [a,f,1,*]

[a] Department of Soil & Environment, Swedish University of Agricultural Sciences, Box 7014, 75007 Uppsala, Sweden
[b] Department of Ecology, Swedish University of Agricultural Sciences, Box 7044, 75007 Uppsala, Sweden
[c] Department of Economics, Swedish University of Agricultural Sciences, Box 7013, 75007 Uppsala, Sweden
[d] Department of Social Sciences, Södertörn University, 14189 Huddinge, Sweden
[e] Department of Environmental Sciences, Aarhus University, 4000 Roskilde, Denmark
[f] Department of Agroecology & Environment, Agroscope, Reckenholzstrasse 191, 8046 Zürich, Switzerland

A R T I C L E I N F O

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A B S T R A C T

Mechanization in agriculture has greatly improved the efficiency of field operations, but also resulted in heavier agricultural vehicles, which has led to increased risks of soil compaction. Hence, farmers benefit from machinery with higher capacity but may suffer from decreased yields caused by compaction. Compaction may result in further environmental costs to society. We present a framework that relates the machinery capacity to soil compaction and its impacts on crop yields and environmental disservices, and associated revenues and costs for farmers and society. We combined simulations using a soil compaction model and a soil-crop model with simple economic analyses. We applied the framework to a case study of cereal production in Sweden, to derive the optimal combine harvester size that maximizes the farmer's private profit and the societal net benefit, respectively. Increased machinery size decreased harvesting costs, but also reduced simulated crop yields and thus crop revenue as a result of soil compaction. Furthermore, in the model simulations, compaction also increased surface run-off, nitrogen leaching and greenhouse gas emissions. Intermediate machinery size maximized the farmer's net revenue. Net benefits for society were highest for the lowest possible compaction level, due to the considerable external costs from soil compaction. We show that the optimal machinery size and thus compaction level for maximum farmer revenue would decrease if either producer prices were higher, harvesting costs savings from larger machinery were smaller, or if farmers were charged for (part of the) environmental costs.

1. Introduction

Mechanization in agriculture has greatly increased the efficiency of agricultural field operations since the middle of the last century. The increase in machinery capacity has also resulted in an ever-increasing weight of agricultural machinery (Schjønning et al., 2015; Keller et al., 2019). For example, the volume of grain tanks of combine harvesters has increased roughly 10-fold during the last six decades, while the wheel load on the front axle of a fully-laden combine harvester has also increased nearly 10-fold (McPhee et al., 2020). A typical wheel load was about 1.5 Mg at the end of the 1950′s, whereas it now exceeds 10 Mg (Schjønning et al., 2015). The increase in machinery weight literally puts soil under more and more pressure. Stresses induced by heavy loads reach deep into the subsoil, thus increasing the risk of subsoil compaction (Alakukku et al., 2003). This is of particular concern because subsoil compaction is persistent due to the low recovery potential of subsoil (Håkansson and Reeder, 1994).

Numerous studies have documented the adverse impacts of soil compaction on crop productivity and soil functions (Horn et al., 1995; Sonderegger et al., 2020; Hu et al., 2021; Obour and Ugarte, 2021). Crop development is directly affected by compaction by increased mechanical resistance in compacted soil, which slows down root growth resulting in reduced nutrient and water accessibility for roots. Compaction-induced changes in pore volume and structure reduce water infiltration, water

* Corresponding author at: Department of Soil & Environment, Swedish University of Agricultural Sciences, Box 7014, 75007 Uppsala, Sweden.
E-mail address: thomas.keller@slu.se (T. Keller).

[1] These authors contributed equally to this work.

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storage capacity, nutrient and water availability and soil aeration, which can result in reduced oxygen and increased carbon dioxide concentrations in soil that impair root growth. In addition to reducing crop yields, soil compaction results in a range of environmental disservices including increased risk of flooding and erosion and higher nutrient losses (Graves et al., 2015; Rogger et al., 2017; Hu et al., 2021). Consequently, the costs of compaction can be divided into costs that directly affect farmers' profits from the same land (e.g. decreased crop yields) and costs to society that do not directly influence the farmer him- or herself (e.g. increased greenhouse gas emissions). The latter are thus so-called externalities, i.e. economic impacts on other parties, which are not reflected in market prices. The sum of these costs constitutes the social cost of compaction.

Although quantifying the exact monetary value of compaction costs remains challenging, especially for off-site costs such as increased greenhouse gas emissions, there is little doubt that compaction results in significant costs to both farmers and society (Graves et al., 2015; Keller et al., 2019). Soil compaction due to agricultural field traffic is considered one of the most severe threats to soil quality in modern agriculture, and soil degradation due to compaction is estimated to affect millions of hectares of arable land worldwide (Flowers and Lal, 1998; Hamza and Anderson, 2005). As much as 170 million ha of land are reported to be affected by soil compaction in Eurasia, resulting in an annual loss of 50 million tons of grain production (Karabayev et al., 2000). For Sweden, Eriksson et al. (1974) estimated that yields of cereals would be 6% higher in the absence of soil compaction. In a more recent study in the U. K., Gregory et al. (2007) reported that severe compaction (eight passes with a 11 Mg tractor) caused wheat yield reductions of 50% in a sandy loam soil. The yields of major crops such as wheat are no longer increasing despite the application of more advanced plant breeding technologies (Reynolds et al., 2012; White et al., 2015). Instead, stagnating yields have been reported in many countries in Europe (Wiesmeier et al., 2015; White et al., 2015), which could be partly a consequence of soil compaction (Keller et al., 2019).

Although the impacts of soil compaction on important agronomic, ecological and hydrological functions are generally well known, and many farmers are aware of the negative consequences of compaction (Thorsøe et al., 2019), the total weights of agricultural machinery continue to increase (Keller et al., 2019). This may be perplexing at first, but can be explained by the relatively large cost-savings arising from the use of large machinery compared with alternative technologies. It is reasonable to assume that farmers strive to use a machinery size which is economically optimal for the farm, given its size and field conditions. Let us consider a simple example, applied to the harvest of a cereal crop. The use of a small harvester would result in little or no compaction and thus ensure high crop yields in the future, but the capacity would be small resulting in high harvesting costs per hectare today. In contrast, a large and heavy harvester increases capacity and hence reduces harvesting costs per hectare today, but might result in significant compaction that would reduce subsequent crop yields and thus future revenues. The optimal harvester size, corresponding to the maximum profits for a farmer, will depend on the balance between the costs for harvesting (machinery and labour costs) and the income from the harvest (e.g. the revenues for wheat yield). In general, off-site compaction costs that do not directly affect a farmer's profits (e.g. costs of flooding, greenhouse gas emissions) do not influence the farmer's decision on the privately optimal machinery size. However, in a societal perspective, these costs should be considered.

The main objective of this study was to present a simple framework that links agricultural machinery size to the degree of soil compaction, crop yields and environmental disservices, and associated revenues and costs for farmers and society. To this end, we combined results from simulations using a soil compaction model (*SoilFlex*; Keller et al., 2007) and a soil-crop model (STICS; Brisson et al., 2008). The outputs generated from the use of these two models were used as inputs for simple economic analyses. We apply the framework to a case study representing conditions in southern Sweden to answer the questions: what is the optimal machinery size and associated degree of compaction when (i) considering only the farmer's private profits and (ii) when accounting also for the environmental externalities, in terms of nitrogen leaching, flooding and greenhouse gas emissions, imposed on the larger society?

2. Materials and methods

2.1. General approach

In this study, we first simulated how machinery size, corresponding to machinery with different total weights, affects soil bulk density. We then used the simulated bulk density profiles as input to a soil-crop model to predict the impacts of traffic compaction on crop yields, runoff, nitrogen leaching, and greenhouse gas emissions. Next, we estimated the costs for harvesting, as well as environmental costs (runoff, leaching, and greenhouse gas emissions) and the revenues from the produced crop. This yielded the net benefits for a farmer and society, respectively, and thus allowed us to obtain the economically optimal compaction level and machinery size. In the following, the procedure is presented in detail. All simulations were made for a case study representing a typical farm in southern Sweden.

2.2. Case study assumptions: loamy soil in southern Sweden

We performed our analyses for winter wheat (*Triticum aestivum* L.) grown on a sandy loam soil (13% clay, 60% sand, 1.7% soil organic carbon content in the topsoil) in Scania county in southern Sweden, which has the largest agricultural area for cereal production in the country.

2.3. Simulating impacts of machinery on soil bulk density

We simulated the impact of combine harvesters of different capacity, corresponding to different wheel loads, on soil bulk density in the uppermost metre of soil with *SoilFlex* (Keller et al., 2007). For this, we used the historical development of the size of combine harvesters during the past sixty years (Schjønning et al., 2015; Supplementary Table S1). Soil mechanical properties were estimated from initial soil bulk density, using relationships developed for Swedish soils given in Keller and Arvidsson (2007). The simulated soil bulk density profiles corresponding to the different machinery sizes served as input for modelling crop yield and environmental impacts, as described in the next section.

2.4. Simulating crop yields and environmental impacts for different levels of soil quality

Yields of winter wheat, N leaching, N_2O and CO_2 emissions, and surface runoff for the different bulk density profiles were simulated using the soil-crop model STICS (Brisson et al., 2008; Coucheney et al., 2015) for 30 consecutive years based on weather data for 1970–1999 obtained from the Swedish Meteorological and Hydrological Institute (SMHI) for the station Barkåkra (56° 29′N, 12° 85′E), which is considered representative for Scania. The climate is humid temperate with a mean annual rainfall of 705 mm and a mean annual temperature of 7.8 °C. Daily precipitation and potential evapotranspiration were used as driving data for the simulations. The latter was calculated by the Penman-Monteith equation from minimum and maximum temperature, solar radiation, wind speed and relative humidity.

A 1.5 m deep soil profile was simulated in STICS, divided into five soil layers (0.05, 0.15, 0.15, 0.45 and 0.7 m thick), with the maximum root depth set to 1 m and an active biological layer 0.22 m in thickness (corresponding to the annual tillage depth). Soil physical properties of each layer in STICS include the water contents at field capacity and wilting point, which we calculated using the pedo-transfer functions developed by Kätterer et al. (2006) for Swedish arable soils. It can be noted that with this approach, the variations in bulk density induced by compaction affect field capacity water content but not the wilting point. In addition to these impacts on hydraulic properties, soil bulk density also affects the root growth simulated by STICS. Root penetration rate is calculated as a piece-wise linear function of bulk density, with two limit values of bulk density; a value below which root elongation is maintained at the maximum rate and a value above which it ceases. The root elongation rate decreases linearly between these two limit values. We set these limiting bulk densities for our soil to 1.1 and 1.9 Mg m^{-3}, respectively, based on published empirical relationships between soil bulk density and penetration resistance (Busscher, 1990), and penetration resistance and root elongation rates (Bengough et al., 2011).

2.5. Costs for harvesting, wheat producer price, and environmental disservices

The annual harvesting cost depends on the type of harvester. If the harvester is purchased by the farmer, the choice depends on the size of the farm. Hence, a farmer with a smaller area of land will avoid large harvesters since this would result in costs of idle capacity. In our case, we are interested in the general relationship between machinery choice and its environmental and economic impact, rather than the implications for farms of different size. We therefore assumed that the farmer can rent harvest services on a per hour basis. The cost for such rental services is determined by the price of the harvester, technical life length, interest rate, and operational cost, where details on data and calculations can be found in HIR (2019) and in the Supplementary material. In this study, we used a linear relationship between harvester wheel load and harvesting costs per hectare (Supplementary Fig. S1). Per hectare harvesting costs decreased with increasing harvester size, primarily because of reduction in the time needed to harvest a given area (Supplementary Fig. S2). For all calculations, we assumed a farm size of 300 ha, which is typical in this region for farms run by farmers engaged in full-time crop production (70% of all arable land in Scania is managed by farms >100 ha; https://statistik.sjv.se/). Moreover, the wheat producer price was assumed to be 1460 SEK/tonne, which is the average for 2015–2019 in Sweden (FAOSTAT, http://www.fao.org/faostat/en/#data/PP).

The unit cost of the environmental externalities were obtained from the scientific literature. The unit damage cost of nitrogen leaching was calculated based on the marginal shadow cost of nitrogen loads for reaching HELCOM's BSAP targets for nitrogen loads to the Baltic Sea, which amounts to 100 SEK/kg N (Gren, 2019). However, only a fraction of the leaching from agricultural land reaches the sea; we assumed a retention of 0.35 which is the average for the catchment in which Scania is located (Hasler et al., 2014), resulting in a unit damage cost for nitrogen of 66 SEK. The damage cost for carbon was calculated from the Swedish CO_2 tax, which is 1190 SEK/tonne CO_2 (https://www.konj.se; https://taxfoundation.org). Flooding damage costs associated with soil compaction for Sweden were calculated to be 55 SEK per hectare agricultural land (Keller et al., 2019). Here, we assumed that this would correspond to an average wheel load (5 Mg), corresponding to a medium size harvester (Supplementary Table S1). Flooding costs were then linearly interpolated as a function of simulated surface runoff, where the surface runoff of the uncompacted reference soil does not result in any flooding costs and the surface runoff for a soil loaded with 5 Mg wheel load results in costs of 55 SEK ha^{-1}.

2.6. Net private and social economic impacts

For each harvester size, we calculated the farmer's profits as the difference between revenues from harvest (i.e. wheat price multiplied by yield) minus harvesting costs. The net benefit for society was calculated as the value of the crop minus harvesting costs and environmental externality costs. We bluntly assumed here that farmers would not care about the environment outside their own farm, which is probably not true. However, we used it here as a simplification that allowed us to reveal optimal machinery size based on the impact on farmers' profits and society's net benefits.

For all calculations, farm size was assumed constant and equal to 300 ha. The optimal harvester size, or in other words, the optimal level of soil compaction, was obtained by plotting profits as a function of harvester size (wheel load). We made additional calculations ("scenarios") to evaluate how the optimal harvester size would be affected if the harvesting costs or the crop revenues (i.e., wheat producer price) changed. Our simulations aim at showing how the optimal machinery size changes: (i) as a function of farmer's harvesting costs and cereal prices, (ii) whether or not environmental costs are accounted for, and (iii) by the cost of environmental externalities.

3. Results

3.1. Impact of machinery size on soil bulk density, crop yield and environmental disservices

Bulk density increased with increasing harvester size (Fig. 1), which is caused by increasing wheel loads with increasing harvester size (Supplementary Table S1). The simulated bulk density profiles agreed well with measured data from a farmer's field in Scania county with a similar texture that is part of an environmental monitoring programme on soil quality (Etana, 2018). The annual average winter wheat yield simulated by STICS was little affected by wheel loads up to 2 Mg, but declined with increasing wheel loads above this critical value (Fig. 2a).

Both simulated surface runoff (Fig. 2b) and nitrogen leaching (Fig. 2c) increased continuously with increases in wheel loads and soil bulk density. The relationship between wheel loads and greenhouse gas emissions (expressed in terms of CO_2 equivalents) showed that maximum emissions were simulated at an intermediate wheel load (4 Mg, Fig. 2d). This is mostly as a consequence of the mineralization of crop residues, which are smaller at larger bulk densities because the mineralization rate is a function of the water content of the soil, which in turn is affected by bulk density. The impacts of different machinery sizes on bulk density, yields and environmental disservices are summarized in Supplementary Table S2.

3.2. Revenues and costs

Revenues are simply the product of crop yield and the wheat producer price. With an average wheat producer price of 1460 SEK per tonne of wheat grains, revenues varied between about 10,120 SEK ha^{-1} in the uncompacted soil and 9670 SEK ha^{-1} for soil compacted by wheel loads of 9 Mg. Harvesting costs decreased with increasing machinery size, due to the higher capacity, and varied from 2200 SEK ha^{-1} for the smallest harvester to 1670 SEK ha^{-1} for the largest harvester. Note that we assume that costs for other inputs remain constant across scenarios.

Societal costs associated with greenhouse gas emissions varied between 3310 SEK ha^{-1} and 3950 SEK ha^{-1}, with the maximum found at an intermediate wheel load (see Fig. 2d). Nitrogen leaching costs increased from about 1290 SEK ha^{-1} for uncompacted soil to 1970 SEK ha^{-1} for the soil compacted by wheel loads of 9 Mg. In comparison, costs associated with flooding, estimated from surface runoff, were small and in the range of 30 to 80 SEK ha^{-1}; however, the basis for the estimation of these costs is uncertain. The environmental costs of compaction were therefore dominated by greenhouse gas emissions. Income, harvesting costs, and the costs of environmental disservices for different machinery weight (wheel loads) are summarised in Supplementary Table S3.

3.3. Optimal machinery size for net revenues

Relationships between machinery size (wheel load) and profits for the farmer are shown in Fig. 3a and for society in Fig. 3b. In our case study, maximum profits for the farmer occur at an intermediate value of

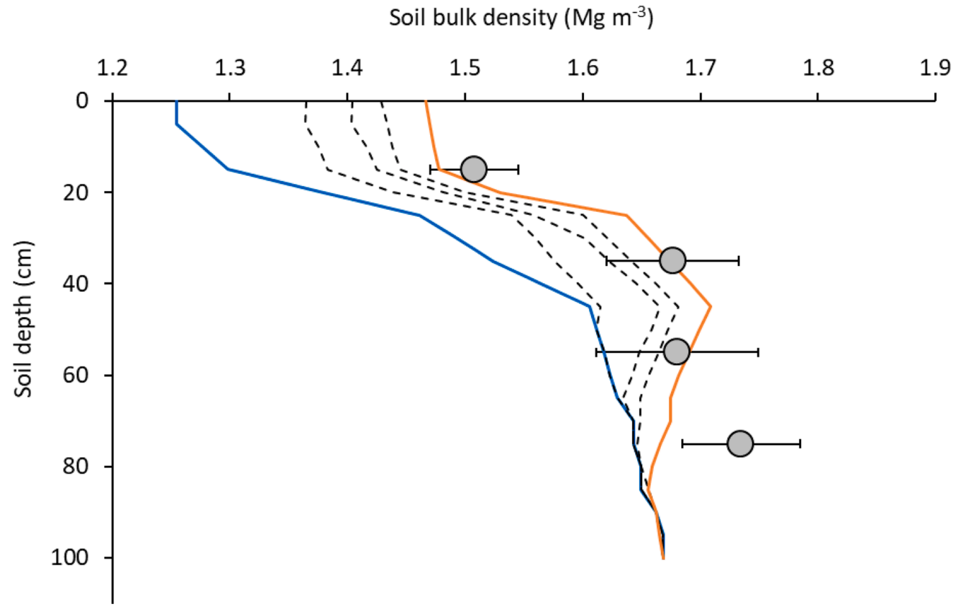

Fig. 1. Simulated soil bulk density (lines) as a function of soil depth for different wheel loads corresponding to different harvester sizes (blue: no compaction, i.e. 0 Mg wheel load; orange: modern harvester with 9 Mg wheel load; black dashed curves: 2, 4 and 6 Mg wheel load), and measured soil bulk density (symbols) in a farmer's field in Scania county. Error bars represent standard deviation of mean.

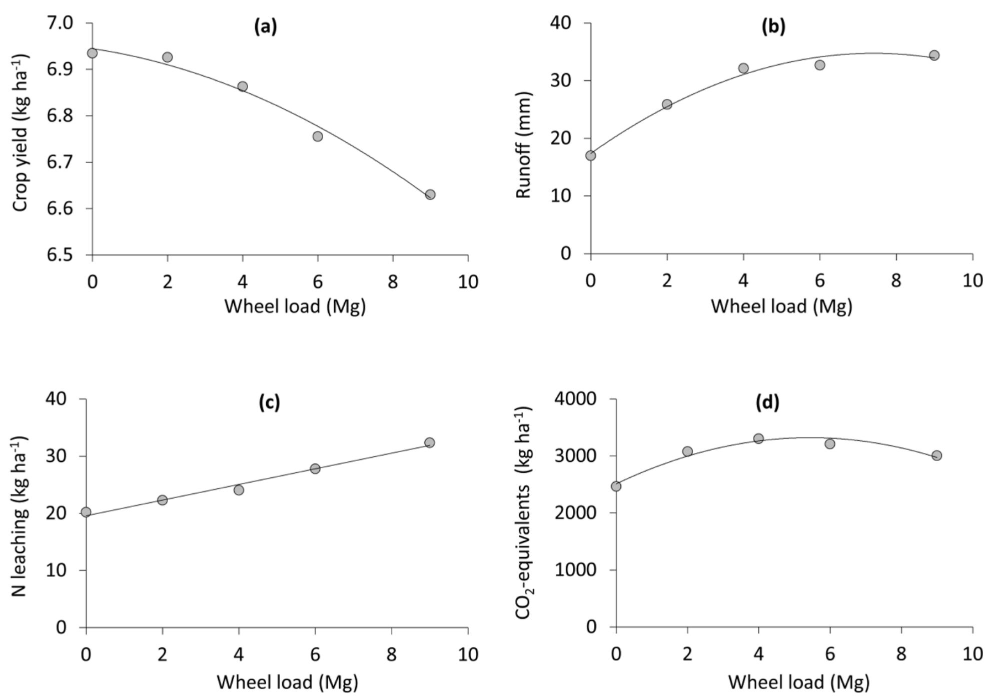

Fig. 2. (a) Impact of soil compaction, expressed in terms of harvester wheel load, on (a) crop yield, (b) surface runoff, (c) nitrogen leaching, and (d) greenhouse gas emissions.

machinery size; the profit to the farmer is smaller when the degree of compaction is either larger or smaller than this optimal wheel load (Fig. 3a). For society, where also environmental costs are considered, net benefits decrease with increasing wheel load up to 7 Mg, and slightly increased again at higher wheel loads (Fig. 3b).

Scenario calculations show that the optimal machinery size is dependent on crop price and harvesting costs (Fig. 4). A lower producer price decreases the influence of crop yield on the balance between revenues from crop yield and the costs of harvesting. As a consequence, a larger harvester (higher capacity) is more advantageous, despite the negative impact on soil physical quality and crop yields, so that the optimal machinery size increases when producer prices decrease (Fig. 4). In contrast, a higher producer price results in a decrease in the optimal machinery size, because the yield penalty resulting from poor soil physical quality becomes more important. Similarly, the optimal machinery size is larger if we assume that an increase in machinery size results in a larger decrease in harvesting costs (and vice versa). The optimal wheel load would also be smaller if farmers were charged for (part of the) costs of environmental disservices, as is evident from Fig. 3a and 3b. For this case study, we found that if farmers were charged more

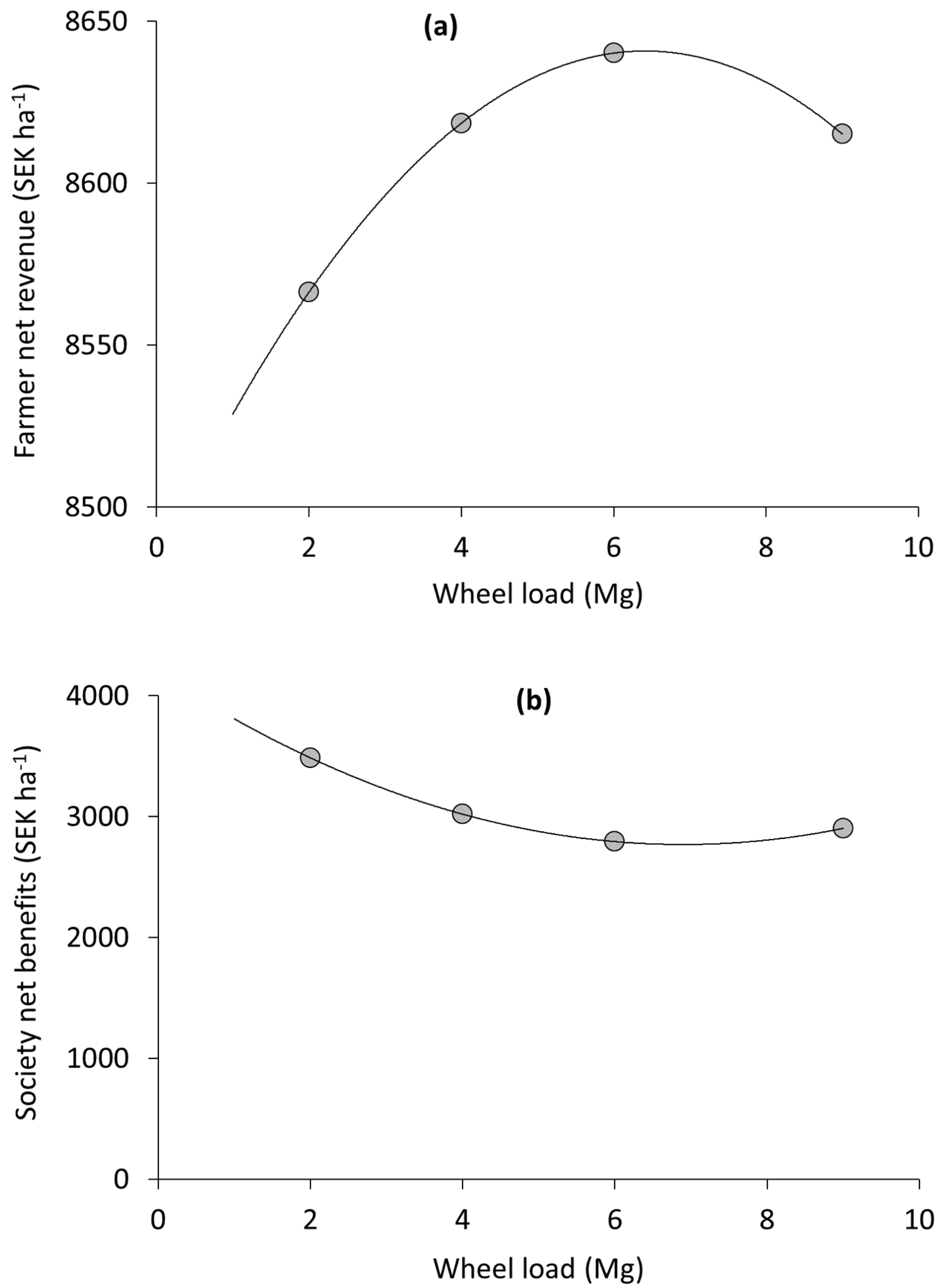

Fig. 3. (a) Farmer net revenue and (b) society net benefit as a function of harvester wheel load.

than 8% of the total environmental costs, the maximum profit to the farmer would be obtained for the lowest wheel load. This is because the environmental costs are much larger than harvesting costs and are also substantial compared with the profits from grain harvest (Supplementary Table S3).

4. Discussion

In this study we used a simple modelling framework to link machinery size to soil compaction, crop productivity and the environmental impacts of crop production, which allowed us to analyse what would be the optimal machinery size and soil physical quality for maximum net revenues. We calculated net revenues for a farmer and for society, where the latter includes the costs of environmental disservices such as nutrient losses (leaching and greenhouse gas emission) and runoff-induced flooding damage. Our current modelling framework is based on a static approach, meaning that a farmer would make a one-time decision for a certain harvester size. This is a simplification as a farmer could choose to switch to a different harvester, by purchasing or renting a new type of machinery. To account for this, a more complex analysis would be necessary, as the life time of the equipment would become an endogenous variable. This could affect harvesting costs for a given type of machinery both when it is owned by the farmer and when it is owned by a company that provides harvesting services. Moreover, the time scales of cost-savings from larger machinery may differ from the time scales of impacts: larger machinery will reduce harvesting costs in the short term, but impacts of soil compaction on crop yield and environmental disservices will occur over a longer time horizon. Future work could therefore implement a dynamic model, where the cost-savings for a given period t due to harvesting with a larger combine are compared with the future reduction in income due to reduced yields and future external costs due to increased soil compaction, and

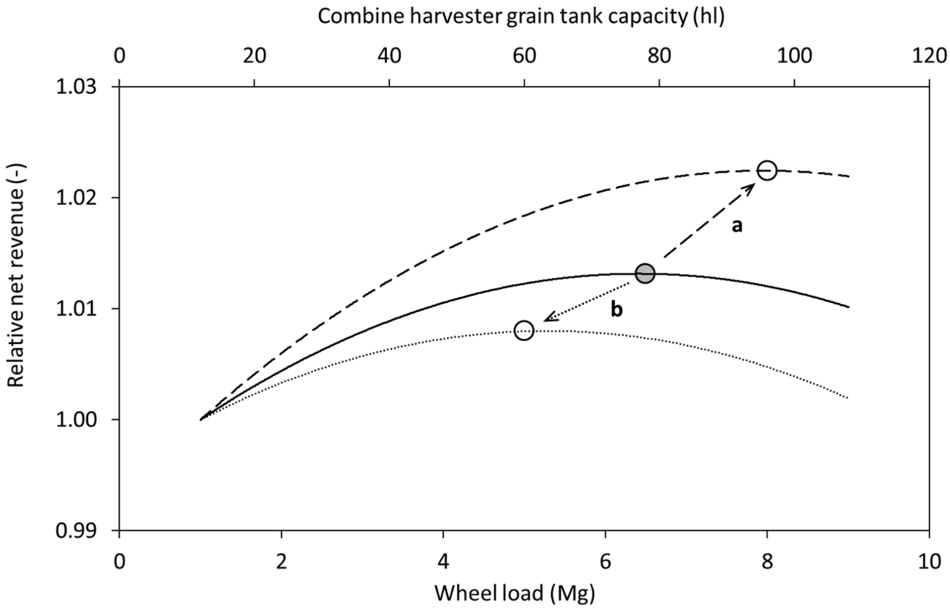

Fig. 4. Relative changes in farmer net revenue as a function of wheel load for three different scenarios; for each scenario, calculations with 1 Mg wheel load serve as reference (relative net revenue = 1.0). Solid curve: baseline scenario, i.e. as in Fig. 3a; dashed curve: 15% lower producer price; and dotted curve: 15% higher producer price. Optimal harvester size for maximum private profit of farmer is indicated for each scenario by circles. Lower producer prices result in larger optimum harvester size (a), while higher producer prices result in smaller optimum harvester size (b).

associated implications for harvester choice over time.

For our case study, we considered a fixed farm size, and we assumed that crops are harvested by buying a service. This situation is realistic for our study area, where expanding farm size is difficult because land prices are high, and high agricultural intensity implies that farmers could hire an agricultural contractor to harvest crops. This business model, where certain field operations are rented from an agricultural contractor – particularly harvest, but also other field operations such as slurry spreading and sowing – is not uncommon in many parts of Europe. A weakness with the present harvest cost calculation is the assumption that it is possible to rent harvest services with different machines. If this is not possible, for example because it is not profitable for the contractor to hold a set of harvesters of different sizes, the cost savings cannot be realized. Also, many farmers own their own combine harvester. In our region, such farmers can in many cases offer a harvesting service to other farmers. In such a situation, the choice of harvester capacity is also influenced by how much additional acreage that could be harvested for other farmers, generating additional income. Similarly, for farmers that are able to buy or rent additional land, the choice of harvester size is influenced by the potential future harvestable acreage. For such cases, a different approach linking harvesting costs and farm size needs to be adopted and adjusted to locally specific conditions.

We simulated compaction induced by combine harvesters and only simulated one crop (wheat, one of the most important crops globally). Harvesters are likely the vehicles with the highest wheel loads in many cropping systems (and therefore could serve as a proxy for mechanization). However, compaction could also be induced by other field operations, either by vehicles with similar or higher wheel loads (slurry spreading, harvest of root and tuber crops), and by field operations involving lower loads but that are typically performed under less favourable (i.e. wetter) soil conditions (e.g. primary tillage during autumn or spring). Future work could evaluate soil compaction based on all field operations during a season, and link this to the revenue of a whole crop rotation, or compare different crops and rotations.

We performed simulations for a soil that is representative for our study region (i.e. Scania), and for which we had data against which we could reality-check the simulations. However, the consequences of soil compaction are dependent on soil texture and initial conditions (as well as on the level of applied stress). The results presented here are therefore dependent on the assumptions made for the setting of our case study and different results are expected for other conditions. A hypothesis would be that compaction impacts on crop yield (Håkansson et al., 1987; Obour and Ugarte, 2021), N_2O emissions (Hernandez-Ramirez et al., 2021) and run-off (Alaoui et al., 2018; Obour and Ugarte, 2021) increase with clay content (while impacts on N leaching may be largely dependent on the level of compaction; Mossadeghi-Björklund et al. 2016), which would reduce income from yield and increase environmental costs, and thus reduce optimum harvester size associated with maximum net revenue. Despite its simplicity, our modelling framework allowed us to see some patterns that should hold true in general – such as the existence of an optimum machinery size for maximum farmer profit, and a smaller optimum machinery size for maximum society net revenue – even though the results in absolute terms, for example for absolute costs or revenues or the optimum size of machinery, likely vary from case to case.

The simulation results were "reality checked" against measured data whenever possible. Simulated soil bulk density profiles agreed well with field monitoring data (Fig. 1). The simulated crop yield losses of ca. 4.4% for the highest degree of soil compaction (wheel load 9 Mg; Supplementary Table S2) are in agreement with the results of field trials on similar soils in Sweden (Eriksson et al., 1974) and with data reported in the literature (for an overview, see Keller et al. 2019). Our simulated nitrogen leaching loads (20–30 kg ha^{-1}year^{-1}; Supplementary Table S2) can be compared with the annual average amount of nitrogen leaching from Swedish arable land of 18.7 kg ha^{-1} and the values of up to 30–50 kg ha^{-1} reported for the south of Sweden (Blombäck et al., 2011, cited in Myrbeck 2014). In our study, we did not account for costs associated with fertilizer production, machinery production, tillage, sowing, or drying of harvested grain, which represent significant energy inputs in cropping systems (Arvidsson, 2010), and which also result in environmental costs.

Our analysis reveals that there is an optimal machinery size, and in this sense an "optimal" soil physical quality, or a certain level of soil degradation that is optimal, in order for farmers to maximize profits (Fig. 3a). In contrast, we show that non-compacted soil, in other words the highest achievable soil physical quality, returns the highest net benefits to society. This is because societal net benefits also consider environmental costs, which increase with increasing degrees of soil compaction (Fig. 3b). Obviously, the relationship between societal net benefits and soil compaction (or machinery size) is dependent on how we value and monetarize food production (crop yield) in relation to the negative environmental impacts of agriculture, and on the spatial scale considered. In our case, environmental costs were mainly associated with greenhouse gas emissions (about 63–72% of the total environmental costs; Supplementary Tables S2 and S3). The costs associated with flooding damage, based here on simulated surface runoff, were in comparison very small (Supplementary Table S3). This could be because flooding from arable land is relatively rare in Sweden compared to hilly or mountainous countries, and possibly because our estimated costs were uncertain (see also Keller et al. 2019). The costs due to flooding are also highly dependent on the values at stake in the surrounding landscape, and how many precautionary or mitigation measures are adopted. One of the most serious consequences of compaction is reduced water infiltration and storage capacity, and it is therefore important to account for damage caused by flooding and erosion in assessments of compaction costs, but further research on the methods for transfer of flooding cost estimates across different sites need to be developed. Hence, the relative importance of different environmental disservices (leaching, emissions, runoff) as well as the total costs should vary significantly between different regions. However, it is intuitively clear that the optimal machinery size is smaller and the optimal soil physical quality is higher if societal environmental costs are also considered than if only the net revenue to the farmer is accounted for, and this should hold true in general.

The optimum machinery size to maximize farmer net revenue is dependent on the harvesting costs and the wheat producer price (Fig. 4). An optimum at higher soil physical quality (less compaction) is achieved if harvesting costs are less sensitive to machinery size (i.e. when the costs do not decrease much with increasing machinery size) or if producer prices are higher. In contrast, more soil degradation results when harvesting costs are more sensitive to machinery size (i.e. larger machinery pays off) or when producer prices are low. The influence of producer price on optimum machinery size and therefore the degree of soil degradation is interesting. When producer prices are low, farmers are less concerned with the yield impact of large machinery. Higher producer prices, in contrast, mean that crop production changes play a larger role for profits. From a soil compaction perspective, our analysis thus suggests that higher food prices may result in better soil physical quality and reduced negative impacts on the environment. However, higher producer prices may also have other unwanted effects such as an increased use of fertilizers and agro-chemicals to boost crop yields, with negative consequences for the environment (Bayramoglu and Chakir, 2021). Another option to prevent soil from degradation due to compaction is to account for environmental disservices (Fig. 3b). The approach we adopted here to combine simple economic analyses with the outputs of soil-crop simulation models should prove useful in supporting the development of policies to sustain or improve soil quality and agricultural production, whilst minimizing environmental disservices.

5. Conclusions

We present a simple framework to evaluate how machinery size and soil compaction levels are linked to net revenue for farmers and society. Increasing machinery capacity, here illustrated using combine harvesters, is associated with lower harvesting costs but also with increasing machinery weights that result in more severe soil compaction. This reduces crop yields and increases environmental disservices in terms of increased nitrogen leaching, greenhouse gas emissions and surface run-off. We applied the framework to a case study representing typical conditions in southern Sweden. We found that there was a privately optimal machinery size, corresponding to an optimal level of soil compaction, at which farmer net revenue is at a maximum. In contrast, the net benefits for society were the highest for the lowest possible compaction level and decreased with increasing machinery size (increasing soil compaction). Environmental costs were primarily associated with greenhouse gas emissions. We found that the compaction level for maximum farmer revenue decreased if either producer prices were higher, harvesting costs savings from larger machinery were smaller, or if farmers were charged for (part of the) environmental costs.

Declaration of Competing Interest

The authors have no conflict of interest involving this study and the findings reported in this paper.

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Supplementary materials

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