Smart Agricultural Technology 4 (2023) 100156

Contents lists available at ScienceDirect

Smart Agricultural Technology

journal homepage: www.journals.elsevier.com/smart-agricultural-technology

Impact of lowered vehicle weight of electric autonomous tractors in a systems perspective

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ARTICLE INFO

Editor: Stephen Symons

Keywords:
Agriculture
Soil compaction
Automation
Simulation
Electric vehicles
Life cycle assessment

ABSTRACT

Modern agriculture rely on heavy machinery that has increased risk of detrimental soil compaction of arable fields. This can lead to negative effects such as reduced yields, reduced field trafficability and increased fuel use. Electric, autonomous tractors makes it possible to replace one heavy machine with several lighter without increased labour costs. In this study, the economic and environmental effects of reduced soil compaction for smaller autonomous tractors were assessed and compared to a scenario with conventional tractors. A discrete event simulation of a Swedish 200 ha grain farm with clay soil was used for the calculations. The electric, autonomous system had lower soil compaction impacts as well as other benefits, and reduced cost in total from 385 to 258 € ha-1 and the climate impact from 270 to 77 kg CO_2eq ha^{-1} compared to the conventional scenario. Soil compaction constituted 20% of the cost and 26% of the climate impact for the conventional scenario. It was concluded that soil compaction was impactful in machinery studies, especially on heavier soil like clay, and should not be omitted. Soil compaction avoidance alone was not impactful enough to warrant a change to electric, autonomous tractors but it reinforced already existing trends and further improved the cost and environmental benefits.

1. Introduction

Sustainable agriculture is required to maintain a stable food supply for a global growing population that is currently being met by intensification of food production. Since 1961, caloric supply per capita has increased by one-third globally, with the use of inorganic fertiliser increasing nine-fold [1]. This increase in food supply has been accomplished through increased machine capacity, with the weight of tractors used in agricultural field operations increasing over time, resulting in static wheel loads increasing from 1000 kg to 4000 kg in the period 1955-2000 [2]. In addition, agriculture is both a contributor to climate change and one of the sectors most affected by it. A study by Lobell et al. [3] indicated a 5.5% reduction in wheat production globally between 1980 and 2008 compared with a case without climate effects. Shukla et al. [1] pointed out several detrimental future effects of climate change on agriculture, such as desertification, increased frequency of extreme weather events, soil degradation and yield reductions, leading to a decisive and lasting negative effect on global food security. Agricultural production contributed 11.2% of total global greenhouse gas emissions in 2010 [4], with around 1% of all global emissions deriving from agricultural machinery use [5], which is almost entirely dependent on fossil fuels.

A proposed solution for reducing machinery-related emissions, including those from heavy non-road machinery, is electrification of drivelines [6]. There are several political goals that target electrification as a key technology, such as a fossil-free vehicle fleet in Sweden by 2030 [7] and a carbon-neutral European Union (EU) by 2050 [8]. Previous studies have reported potential for electric agricultural machinery to be cost-competitive [9,10] and environmentally beneficial [11,12] compared with conventional vehicle systems. In order to maintain economic viability and reduce drawbacks with electric drive, vehicle autonomy has been proposed as a synergetic technology solution and key driver [6]. Autonomy maximises the time in which the vehicle can work in the field, while reducing the detriment of longer charging periods by reducing operator costs and allowing for more work hours per day. As an indirect effect, it is possible to work with multiple lighter vehicles instead of a single larger machine, with equal or improved performance. In addition to influencing the cost and environmental impacts, switching to self-driving and electric vehicles can lead to lighter vehicles, which might have a beneficial effect on soil health due to the

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https://doi.org/10.1016/j.atech.2022.100156
Received 3 October 2022; Received in revised form 9 December 2022; Accepted 10 December 2022
Available online 13 December 2022

reduced load, as there is a link between vehicle weight and soil compaction.

Soil compaction involves a reduction in soil volume, specifically in the air-filled fraction, and an associated increase in bulk density [13,14]. Causes of unwanted soil compaction include increasing machine weight, intensive cropping, short crop rotations, overuse of machinery and inadequate soil management [15]. The rate of soil compaction is increasing globally [16] and problems have been reported worldwide [15]. Soil compaction has several separate or interconnected effects on agriculture, such as decreased water conductivity [17], decreased plant growth, reduced fertiliser efficiency, lower crop yield and increased machine use due to increased soil density [18], all of which can be detrimental to agricultural production and the environment. Long-term cereal yield losses from soil compaction are estimated to be 4-20% [2,16, 18,19]. According to Graves et al. [18], soil compaction imposes an annual cost to agricultural production in England and Wales of 200 M€ y^{-1}, or 56-140 € ha^{-1}. In the same study, the mean annual cost of soil erosion in Europe was estimated to be 122 € ha^{-1}. Keller, et al. [2] and Hamza and Anderson [15] reported that roughly one-third of arable land in Europe (33 Mha) was negatively affected by soil compaction in 1991, and the proportion has likely increased since then, with Keller and Or [20] suggesting that 20% of the global arable land is at risk of chronic subsoil compaction. Chamen et al. [19] estimated that mitigating soil compaction could increase gross margin by 22 £ ha^{-1} and avoiding soil compaction could increase gross margin by up to 118 £ ha^{-1} for clay soils. Previous life-cycle assessment (LCA) studies of soil compaction concur that it has a significant environmental impact, mainly related to reduced yield levels [21,22] and increased nitrous oxide (N_2O) emissions due to poor soil aeration [19].

Some previous studies [19,23,24] have proposed use of lighter machines as a soil compaction avoidance strategy, but have pointed out that autonomous operation will be needed to make lighter vehicles economically interesting to farmers. Other studies have also suggested that electric field tractors require autonomy to compete economically with contemporary conventional tractors, which also allows them to be lighter [10,25]. This indicates the possibility of a synergetic solution where vehicle autonomy addresses both concerns. When modelling the effects of soil compaction, previous works have focused separately on the physical system [26], economic cost [2,18] or environmental effects [21]. Soil compaction is often not considered in machine analysis, but its inclusion has been recommended [10].

By studying in parallel all direct and indirect effects of a system change on the performance, economics and environmental impact of an agricultural machine system, a greater understanding can be reached and more informed recommendations can be made. The aim of this study was to extend previous work studying the change from diesel tractors to self-driving electric tractor systems by including soil compaction effects and assessing the general economic and environmental impacts. This was done through simulations of vehicle systems in Swedish agriculture. The hypothesis tested was that use of lighter machines, made economically competitive by self-driving technology, can reduce soil compaction, with beneficial economic and environmental effects.

2. Material and methods

The analysis comprised dynamic discrete-event simulation of a 200-ha farm in Uppland, Sweden, growing four different kinds of cereal (winter wheat, spring wheat, barley and oats). Soils in the Uppland region have a high clay content, typically 40-60% [27]. The simulation included tractor parameters, soil data, weather effects and output time requirements, delays, energy use and machine logistics. Soil compaction effects were also included in the model and the resulting output was quantified (Fig. 1).

The results from the model were used to calculate total annual cost of operation, using a method described by Wu, et al. [28] and Lampridi et al. [10], together with straight-line depreciation and average interest rate methods, combined with an economic model previously used in Lagnelöv et al. [9]. The results were also analysed in an environmental LCA study using the ISO methodology [29], characterisation factors from the ReCiPe method [30,31] and inventory presented in [11]. In addition, only changes directly related to a change in tractors were included, so the harvest, inputs, seeds and implements were omitted due to the assumption of having the same cost and environmental impact in all cases.

The focus in the analysis was on long-term subsoil compaction, rather than shorter-term topsoil compaction. Any change in machine systems would mainly affect the subsoil over a certain time horizon and the scope of this study was therefore that time horizon. According to Hamza and Anderson [15], topsoil compaction is caused mainly by ground pressure and can therefore be lessened by increasing the tyre-soil contact area, while subsoil compaction is related to the axle load and can be lessened by decreasing vehicle weight.

A difficulty when modelling soil compaction is that most arable land in modern agriculture is already compacted to some degree [2,18], so data on yield levels and vehicle energy use already implicitly include losses from soil compaction, preventing comparison to a vehicle system with no soil compaction effects. Keller et al. [2] argue that most field trials compare normally compacted soils (arable land trafficked in a normal manner) with experimentally compacted soils, since most agriculturally managed soils are at least partly compacted. Therefore yield penalties identified in the literature derive from further compaction of already compacted soil and not compaction of uncompacted soil (also known as virgin soil or not trafficked soil) [2]. For ease of presentation

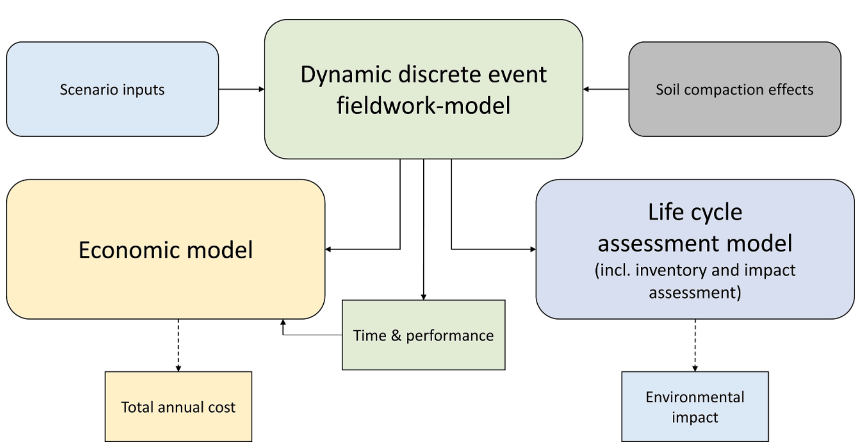

Fig. 1. Overview of models (oblongs), their interconnections (arrows) and inputs/outputs (rectangles).

and for comparison with literature data, this study made the same assumption, using normally compacted soil as the baseline and allocating the negative effects of further soil compaction to scenarios with heavily compacted soil due to high vehicle weight.

2.1. Model input and scenarios

Model input to the different scenarios compared, encompassing different technology pathways, is shown in Table 1. To assess the impact of soil compaction, heavy and light vehicles were considered and electric and diesel tractors, which were either manned or autonomous.

The simulation considered a conventional cropping system for grains, including cultivation, harrowing, roller packing, sowing, fertilisation, spraying and ploughing. The tillage depth was 10 cm, except for ploughing where it was 20 cm [32]. A soil with a high (>40%) clay fraction was assumed. The tractors were simulated to only work when the soil moisture content was under the limit for workability from de Toro and Hansson [33], which was assumed to be 85% of field capacity for general tillage and 110% of field capacity for ploughing, using field capacity from Witney [34].

Two scenarios with a single diesel-powered 250-kW tractor weighing 10,800 kg were included as the current state of technology, to which all other scenarios were compared. In one of those scenarios, the tractor was assumed to have an autonomous system, but it was otherwise identical to the other conventional tractor scenario. A scenario with a large electric tractor was included to analyse the difference between one larger machine and several smaller machines. The main alternative scenario assumed two 50-kW electric autonomous tractors, each weighing 4047 kg, of which 1000 kg was batteries, as in Lagnelöv et al. [11]. This solution has been shown previously to be competitive in several metrics [9,11,25]. For comparative purposes, a similar scenario with two 50-kW autonomous tractors with diesel as fuel was also included. A final scenario where three electric machines were used was included to assess a scenario with high operational capacity and rate of work.

Energy use in the electric scenarios was based on fieldwork force equations from [35], adjusted down by 15% to fit field test results since the original equations have been reported to overestimate energy use [36,37]. The diesel scenarios used data from field tests performed in the Uppland region [38], leading to diesel energy consumption for 200 ha of mixed cereal cropping of 108,803 kWh y^{-1} (or 54 L ha^{-1} y^{-1}) for normally compacted soil and 151,978 kWh y^{-1} (76 L ha^{-1} y^{-1}) for heavily compacted soil. The diesel energy consumption for heavily compacted soil was calculated using the increase in fuel use presented in Section 2.2.3.

2.2. Soil compaction and vehicle weight

Tractors with high weight have been found to cause elastic deformation in soil, with the effect persisting in layers deeper than 40 cm after the pass if total vehicle weight exceeds 8000 kg [15,39]. It has been shown that tractors with weight below 5300 kg only compact the top 40 cm of soil [39,40]. Compaction in the topsoil (0-25 cm) can be seen as reversible within one or a few years, while the mid soil level (25-40 cm) remains compacted for up to 10 years and compaction occurring below 40 cm is considered to be very long-lasting or permanent [21,22,41] (Fig. 2).

In the comparison in this study between heavier (10,800 kg) and lighter (3-400 kg) vehicles, it was assumed that the tractors with lower weight compacted the soil in a reversible way, while the heavier machines led to long-lasting or irreversible soil compaction (in practice, the effect of vehicle weight on soil compaction is more gradual). This is in agreement with recommendations from Horn and Fleige [42], who recommended an axel load of under 3300 kg to avoid long-term subsoil compaction. The focus in this study was mainly on long-term soil compaction effects resulting from making a lasting change in machinery systems, but the effects of temporary soil compaction are touched upon in the discussion.

Among the many adverse effects of soil compaction, three were considered in the present analysis: 1) reduced trafficability due to a reduction in soil hydraulic conductivity, 2) reduced crop yield due to rooting difficulties; and 3) increased fuel use due to increased soil density/resistance. These factors are directly related to vehicle systems and have been identified as impactful [2,15,23,44].

2.2.1. Reduced hydraulic conductivity

Soil compaction results in a reduction in soil hydraulic conductivity at saturation (K_{sat}), which leads to slower drying of the soil and subsequently a narrower window of trafficability [43]. Keller et al. [2] found that the hydraulic conductivity decreases linearly with increasing soil compaction and estimated that the average hydraulic conductivity of subsoils (0.25-0.7 m) is 40% lower for managed arable soils than unmanaged soils. In a field study by Keller et al. [17], a decrease of three

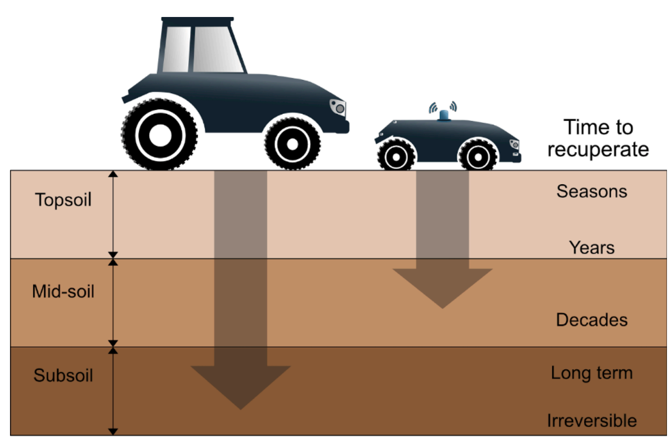

Fig. 2. Graphical overview of soil compaction at different depths and for different vehicle weights [21,23,43]. Soil compaction depth shown as grey arrows.

Table 1
Input to the model of key parameters in the different scenarios. Batteries and vehicle weights from Lagnelöv et al. [11], with assumed battery gravimetric energy content of 0.1 kWh kg^{-1}.

Scenario no.	Fuel	Number of vehicles (N_v)	Rated power (P_r, [kW])	Energy carried [kWh, (l)]	Extra battery packs	Working time [h d^{-1}]	Mass, incl. batteries [kg]
1	Diesel	1	250	4684 (463)	-	10[a]	10,800
2		1	250	4684 (463)	-	24[b]	10,800
3		2	50	1315 (130)	-	24[b]	3047
4	Electric (Battery Exchange	2	50	100	2	24[b]	4047
5	System)	3	50	100	2	24[b]	4047
6		1	250	200	2	24[b]	12,800

[a] Manned
[b] Autonomous.

orders of magnitude in K_{sat} was observed in the topsoil directly after a compaction event. After two weeks, a 74% reduction of K_{sat} remained. Assuming that this finding is indicative of changes in saturated hydraulic conductivity in general, this would lead to a reduction in K_{sat} from 21.3 mm d^{-1} to 5.5 mm d^{-1} using the soil parameters and soil moisture balance equation from Witney [34] as in Lagnelöv, et al. [25]. In our model, K_{sat} was mainly relevant for the drainage rate of the soil. For heavily compacted soil a hydraulic conductivity constant of 5.5 mm d^{-1} was used, while for normally compacted soil the base value for clay soils (21.3 mm d^{-1}) in Witney [34] was used. The heavier vehicles (10.8 tonnes) were assumed to give rise to semi-regular compaction events when following normal agricultural practise, as described by [2], and the value for compacted soils was applied. The lighter vehicles (3-4 tonnes) were assumed to only cause reversible levels of compaction already included in yield data from empirical sources.

2.2.2. Reduction in crop yield

The focus in this study was on long-term yield loss as an effect of choice of machinery system. A constant annual yield loss of 8%, as stated in Keller et al. [2] for Swedish soil with high clay content, was assumed for the heavy vehicles. No loss of yield was assumed for the vehicles with lower weight, as the soils were assumed to be normally compacted and normal yield data applied. Some studies suggest time-dynamic recovery of yield levels after compaction events [2,22,39], but this was beyond the scope of the present study. Yield losses were re-calculated to a direct economic cost, using the data in Table 2.

2.2.3. Increased fuel use due to higher soil density

Soil compaction leads to an increase in soil density, which necessitates either higher-powered (and heavier) machinery or more passes, both leading to an increase in fuel consumption compared with less compacted soil [21]. Graves et al. [18] assumed an 87% increase in use in fuel energy for all seedbed preparation operations on clay soil. In this study, it was assumed that harrowing, ploughing and cultivation were affected by soil compaction, while seed drilling, roller packing, and fertiliser and pesticide spreading were unaffected.

2.3. Economics

The economic calculations were based on the model for total cost of ownership described in Lagnelöv et al. [9], with the size of fuel tanks updated to reflect common practice (Table 1). The model was used to assess the total annual cost of owning and using fieldwork vehicle systems, including investment cost, maintenance and repair, capital costs, fuel use, operator cost and the economic effect of soil compaction. Several cost factors normally included in agricultural cost assessments were assumed to be similar for all scenarios and omitted from the detailed calculations. These included the farm itself, vehicle housing, insurance, inputs, implements and seeds. The cost of infrastructure for diesel refuelling was omitted, as such infrastructure was assumed to be already present on-site, but the installation cost of electric refuelling infrastructure (charging stations and battery exchange systems) was included, as very few farms have this infrastructure yet.

The autonomous vehicles were assumed to be capable of operating by themselves, but requiring oversight or some degree of handling for a fraction of the operating time, with this fraction varying for different tasks. This meant that even the autonomous vehicles had an operator cost that increased with increasing active time. It was assumed that 10% of charging, 20% of fieldwork and 30% of road transport needed oversight by an operator [9].

The electricity price was calculated as a three-year average (2018-2020) for an industrial consumer with yearly consumption of 50-200 MWh and the total price, excluding VAT, was 0.076 € kWh^{-1} [49]. Diesel prices were taken from [50,51] and aggregated as a three-year average (2018-2020) to match the time period of the electricity prices, resulting in a pump price of 1.42 € L^{-1}. These prices were modified with the Swedish tax reduction for agriculture from energy and CO_2 taxes and VAT exemption (normally 25% on production costs and taxes). The tax reduction was 178 € m^{-3} (1930 SEK m^{-3}) at the start of 2022, but a new level of 363 € m^{-3} (3930 SEK m^{-3}) has been proposed from 2022 by the Swedish government [52] and was used in this study. It results in an effective diesel price for Swedish farmers of 0.77 € L^{-1}, or 0.076 € kWh^{-1} using conversion factors from Reif and Dietsche [53].

Table 2
Field and grain yield data used in the study. Yield is 3-year average for Uppsala, 2019–2021 [45–47], and grain prices are 5-year (2017-2021) aggregated means from selected wholesale buyers [48].

	Winter wheat	Spring wheat	Barley	Oats
Yield [kg grain ha^{-1}]	6809	4557	4847	4321
Wholesale price [SEK kg^{-1}]	1.65	1.76	1.57	1.36
Wholesale price [€ kg^{-1}]	0.152	0.163	0.145	0.125
Revenue [€ ha^{-1}]	1,036	741	702	542

2.4. LCA

The environmental assessment took the form of consequential LCA, following the ISO 14040:2006 standard methodology [29]. The scope of the assessment was production and assembly, use and end-of-life (EoL) phases of the life cycle for the different vehicle scenarios considered. The focus was on the vehicle systems performing field operations. Inputs, seeds, implements and harvesting were omitted. The method presented in [11] was followed, with the same assumptions, sources and inventory. The ReCiPe method [30,31] was used for characterisations and weighting in life cycle impact assessment (LCIA), applying the hierarchist perspective as it is the default for the method and hence commonly used. Modelling and calculations were performed in the LCA software SimaPro (v.9.0.0.49, PRé sustainability, Amersfoort, The Netherlands). The inventory (Table 1) was made using the models from [11]. The infrastructure was assumed to be scaled proportionally, i.e. larger battery pack size required a larger battery exchange system.

The LCA results were calculated for the midpoint global warming potential (GWP) impact factor and for the aggregated damage categories human health, ecosystem impacts and resource scarcity. GWP is the most commonly presented metric for battery electric vehicles and the damage categories give a holistic picture of the environmental impact, using all 18 impact categories available in SimaPro. Supplementary material S.1 shows the results for the 18 midpoint and endpoint characterisation factors and the damage categories, and an aggregated single score for all vehicle system scenarios considered.

The LCA included vehicle, fuel and additional fuel use. The vehicle category included production, assembly, maintenance, repair and EoL for the vehicle, batteries and charging infrastructure. The assessment of fuels showed the impact originating from the use of diesel (with no blend-in biofuels) or electricity (Swedish marginal electricity) [54,55].

2.5. Sensitivity analysis

As the simulations and calculations required assumptions and aggregation of models with different levels of detail and certainty, a nominal range sensitivity analysis (also known as once-at-a-time sensitivity analysis) was performed for key parameters in vehicle performance, cost and environmental impact. Some alternative values or scenarios of certain interest were also explored and the resulting effects calculated. Since the models used are deterministic and the main objective of the sensitivity analysis was to find the most impactful parameter, the analysis method chosen to verify and validate the results is in line with recommendations [56,57]. As in Lagnelöv et al. [11], the analysis was performed for absolute change (change in the base unit), absolute sensitivity (change in percent) and relative sensitivity (change per percent) Eqs. (1)–((3)):

$$\Delta_V = P(V_\Delta) - P(V_0) \tag{1}$$

$$S_A = \frac{\Delta_V}{P(V_0)} = \frac{P(V_\Delta) - P(V_0)}{P(V_0)} \tag{2}$$

$$S_R = \frac{S_A}{\Delta_P} \tag{3}$$

where Δ_V is the absolute change, $P(V_\Delta)$ is the resulting value after the parameter change, $P(V_0)$ is the base value, S_A is the absolute sensitivity, S_R is the relative sensitivity ($\%^{-1}$) and Δ_P is the fractional change in the parameter. The results were presented as change in GWP and in total annual cost.

3. Results

The selected scenarios were simulated and analysed to determine the effects of different factors. The economic, environmental and performance results are presented, with the impacts of soil compaction being described specifically.

3.1. Effects of soil compaction

3.1.1. Reduced hydraulic conductivity

Soil with hydraulic conductivity of 21.3 mm d^{-1} (normally compacted soil) and 5.5 mm d^{-1} (heavily compacted soil) was simulated over a 30-year period (1988-2018), with the soil moisture content (m_a) determined. Two thresholds for fieldwork were included in the vehicle system model, one for general tillage and one for ploughing. If the soil had lower m_a than the trafficability threshold, the tractors were able to perform the selected operations in the field without damaging the soil. The results showed that with less compacted soil, the average time suitable for ploughing increased from 73% to 82% and the average time suitable for general tillage increased from 48% to 49%, i.e. there was a greater effect on ploughing than general tillage (Fig. 3). However, the greater difference for ploughing had a relatively small effect on overall performance of the system, as much more time was spent on general tillage and ploughing had a wider allowed window of operation. In addition, ploughing was the last operation before the season end for all crops except winter wheat and was therefore less time-critical than other operations.

3.1.2. Delay and changes in trafficability

Fig. 4 shows the time taken to complete all assigned operations in a certain growing season and the fraction of total time required by each operation. Soil compaction caused an increase of 1-3 days over the entire working year, mainly due to decreased saturated hydraulic conductivity leading to longer waiting times for favourable in-field driving conditions. The start of the time-critical spring season was delayed by on average 1.2 days by soil compaction, but this change was less than the variation between years and was assumed to have had a minor effect on the driveability and performance of the vehicle system. The autonomous diesel scenarios all had a significantly lower time requirement, 43-50 days compared with 96 days, but spent a higher proportion of total time working, 37-40% compared with 19% for the manned scenario. It is important to note that the absolute amount of time required to perform fieldwork was similar for all scenarios, but the total time varied as non-productive time (resting time for operator, charging, farm-to-field transport) varied from scenario to scenario. The fraction of time spent waiting for drier fields (denoted "weather" in the figure) remained fairly constant between the scenarios at 49-57%, and the decrease in hydraulic conductivity in compacted scenarios had only a minor effect on the value.

The electric vehicle scenarios generally had a higher time requirement than their diesel counterparts, but showed similar working capacity to the manned diesel scenario, both in overall time and in the time-critical spring season. They had a lower work rate than the top diesel system, but still showed adequate rate of work and the fraction of time spent on fieldwork was similar to that for the manned diesel

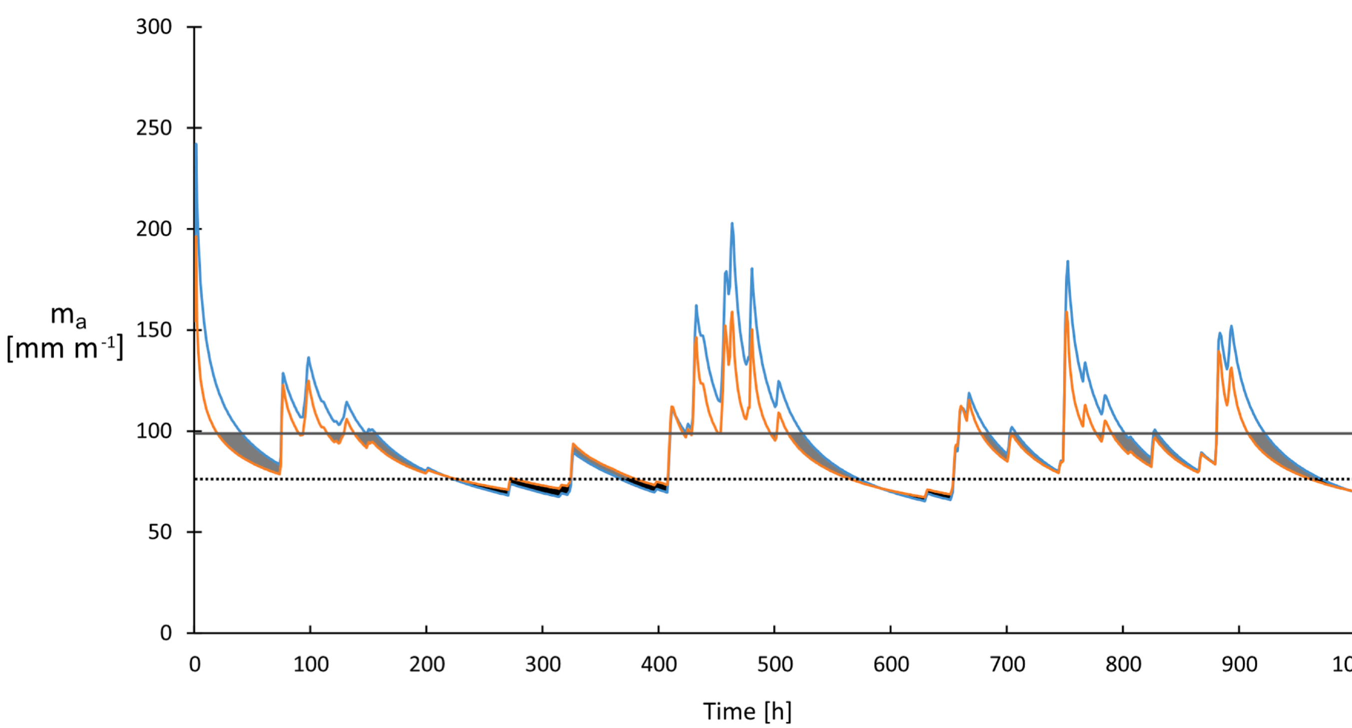

Fig. 3. Soil moisture content (m_a) during the first 1000 h of the growing season in 2016. Two values of soil saturated hydraulic conductivity are shown, for heavily compacted soil (K_{sat} =5.5 mm d^{-1}, blue line) and normally compacted soil (K_{sat}=21.3 mm d^{-1}, orange line). The trafficability limits for general tillage (black dotted line) and ploughing (grey solid line) are indicated. Differences between the two compaction scenarios are shown in grey (for ploughing) and black (for general tillage).

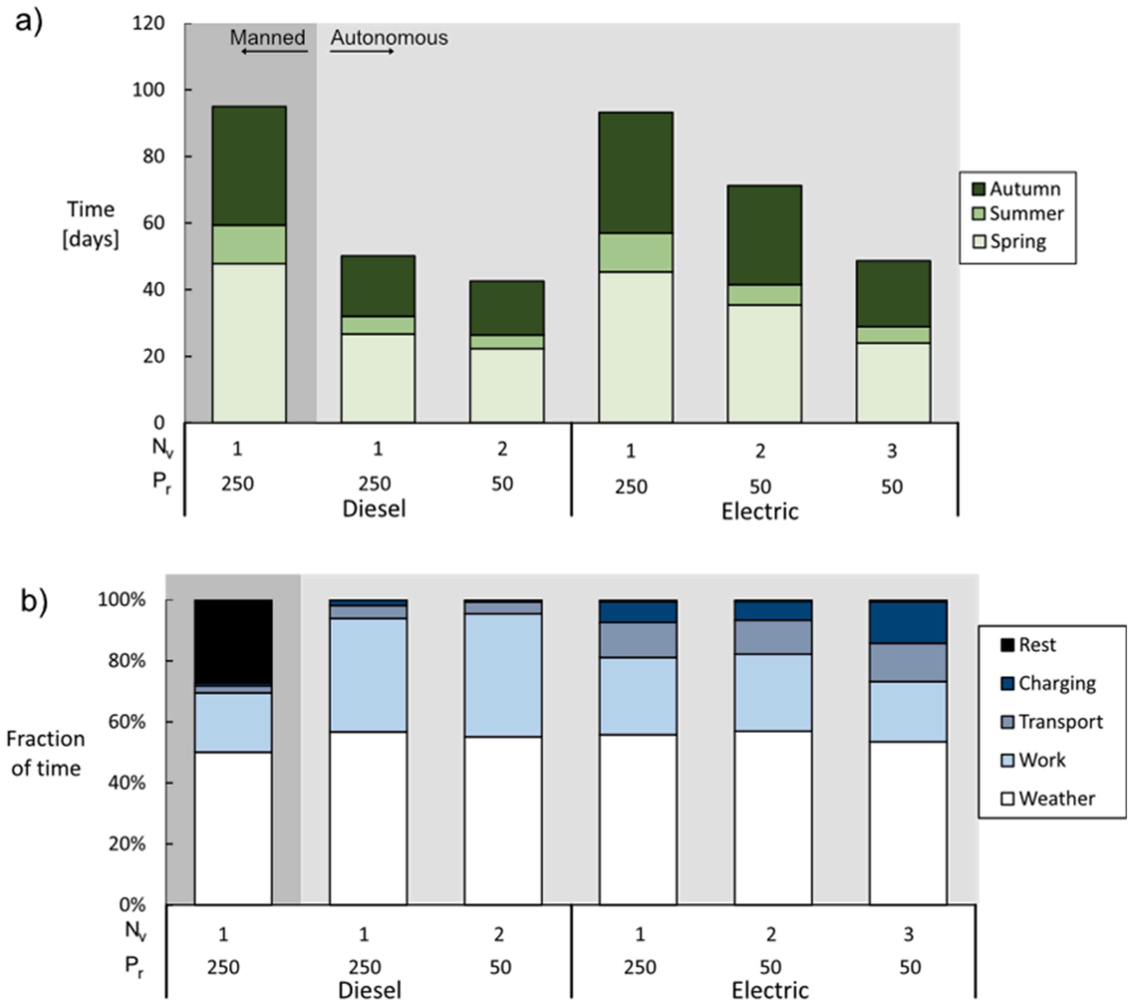

Fig. 4. Results of scenario analysis for six scenarios differentiated by number of vehicles (N_v) and rated power in kW (P_r). (a) Length of working periods, with the conventional diesel scenario serving as an estimate of adequate capacity, and (b) fraction of time spent in different operational modes. All values are 11-year averages (2008-2018). Manned (10 h d^{-1}, dark grey) and autonomous (24 h d^{-1}, grey) operation are indicated as background fields.

system, which served as a baseline for adequate capacity (Fig. 4).

3.1.3. *Reductions in crop yield*

The yield loss and average yield for the different cereal crops in the system are shown in Fig. 5. The reductions in crop yield calculated based on values in Keller et al. [2], assuming a 8% yield loss, were converted into cost normalised per hectare of arable land and compared with literature values (Table 3).

3.1.4. *Increased fuel use due to higher soil density*

Dynamic discrete-event simulation of the vehicle system showed that for the conventional diesel tractor, the increased soil compaction caused an increase of 29% in both energy consumption and fuel cost, due to the increased energy use for tilling in heavily compacted soils. For a battery-driven tractor of the same rated power and general weight, fuel use increased by 30%.

3.2. *Economic impact*

The combined effects of soil compaction varied for the different vehicle systems and individual effects also affected different parts of the cost analysis. Decreased hydraulic conductivity increased the amount of time required to perform all field operations, thus increasing the operator costs and the timeliness cost (the cost of not establishing the crop at the optimal time).

For the diesel scenario, the cost difference between normally and heavily compacted soil was 78 € ha^{-1} y^{-1}, with most of the cost coming from yield loss (78% or 60.4 € ha^{-1} y^{-1}) and increased energy use (22 % or 17.1 € ha^{-1} y^{-1}). Increases in timeliness and operator costs were close to negligible. For the scenario with an electric tractor of the same size and power, the cost of soil compaction was 71 € ha^{-1} y^{-1}, divided into 85% yield loss, 12% increased fuel use and 3% timeliness cost.

These values were used to calculate total annual cost of the systems (Fig. 6). The annual cost varied greatly between the different scenarios, with the heavier vehicles having the highest annual costs. The 250-kW diesel tractor had the second highest cost, 385 € ha^{-1} y^{-1} (77,000 € y^{-1}), with 78 € ha^{-1} y^{-1} or 20% being attributable to soil compaction through higher fuel use or yield losses. Making this tractor autonomous reduced this cost to 306 € ha^{-1} y^{-1}, mainly by reducing the operator and timeliness costs. The highest cost was seen for the 250-kW electric tractor, 421 € ha^{-1} y^{-1} (84,163 € y^{-1}), of which 71 € ha^{-1} y^{-1} (17%) was attributable to soil compaction (Fig. 6).

The electric scenarios generally had a higher annuity, as they needed higher initial investment, but in return had lower maintenance and fuel costs. Compared with the diesel scenarios, the electric scenarios with smaller vehicles showed a 46-62% reduction in fuel costs (Fig. 6). The scenario with two 50-kW electric autonomous tractors had an annual cost of 258 € ha^{-1} y^{-1}, with annuity and timeliness being the main costs. The scenario with three 50-kW vehicles had a cost of 273 € ha^{-1} y^{-1}, reducing the timeliness cost compared with the two vehicle system by

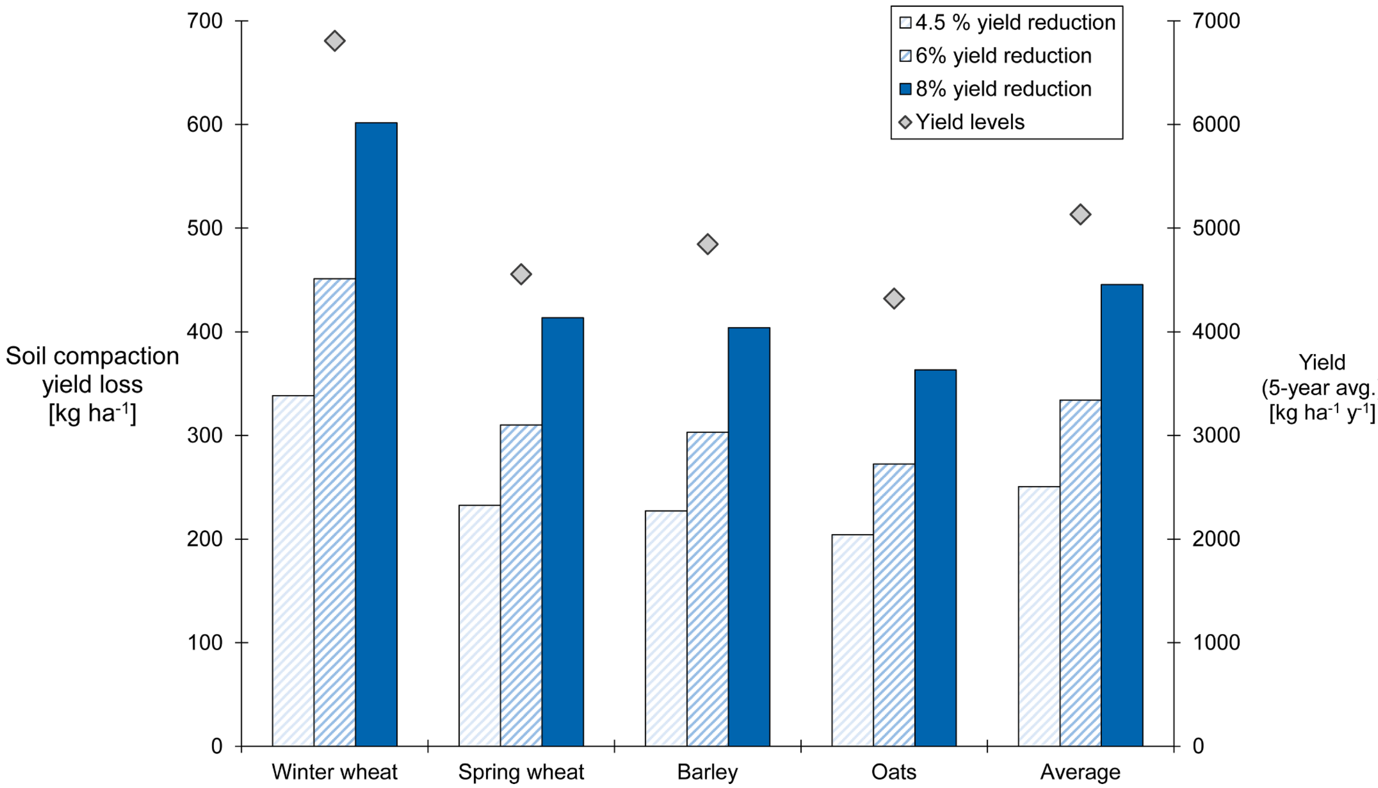

Fig. 5. Yield loss levels due to soil compaction (left axis), for different cereal crops and for all four cereal crops in the system studied, based on yield loss levels from the literature [2,18]. The 8% loss assumed in simulations is shown as solid blue bars, while alternative levels are shown as cross-hatched bars. Actual yield levels (right axis) are shown as grey diamonds.

Table 3
Cost normalised per hectare of arable land of simulated yield losses due to soil compaction for the individual cereal crops and for all four cereal crops in the system studied. Proposed yield loss levels from the literature [2,18] are shown for comparison. Values from Table 2 were used in the calculations. The values from Graves et al. [18] are adjusted for inflation.

Yield reduction level	Cereal crop					Notes
	Average, all cereal crops	*Winter wheat*	*Spring wheat*	*Barley*	*Oats*	
4.5 % [€ ha^{-1}]	34.0	46.6	33.3	31.6	24.4	Suggested value for light soils [18]
6% [€ ha^{-1}]	45.3	62.2	44.5	42.1	32.5	Swedish average for 25-40% clay [2]
8% [€ ha^{-1}]	60.4	82.9	59.3	56.1	43.3	Suggested value for >40% clay [2]
Average for all cereals [€ ha^{-1}]	49.8					[18]

increasing the annuity. Compared with the conventional diesel scenario, this represented a cost reduction of 29%. The lowest cost was seen in the scenario with two small, light autonomous diesel tractors, which were light enough not to incur any penalty from soil compaction and did not have the large initial investment needed in the electric scenarios. They had a cost of 196 € ha^{-1} y^{-1}, a reduction of 49% compared with the conventional diesel scenario.

3.3. Life cycle assessment

The LCA results showed that the electric, autonomous vehicle systems had a lower impact in terms of GWP, human health, ecosystem impact and resource scarcity than the diesel vehicle, except for the 50 kW diesel vehicle in the "ecosystem impact" damage category. The conventional 250 kW diesel scenario (which included soil compaction) had GWP of 270 kg CO_2eq ha^{-1} y^{-1}, of which 241 kg CO_2eq ha^{-1} y^{-1} (89%) originated from the fuel. In particular, 26% of the total GWP impact was due to increased fuel use because of soil compaction. The smaller diesel vehicle system with two 50-kW tractors and normally compacted soil had GWP of 188 kg CO_2eq ha^{-1} y^{-1}, of which 170 kg CO_2eq ha^{-1} y^{-1} (90%) derived from fuel use. The total GWP for the electric vehicles was 77-143 kg CO_2eq ha^{-1} y^{-1}, of which 55-67% was due to fuel use in the electric vehicles (Fig. 7).

The general trend was the same for the three damage categories, with the electric scenarios having lower impact overall but a higher impact in the vehicle category, mainly because of battery manufacture (Fig. 7). Soil compaction led to a 26-27% increase in the damage categories for the 250-kW diesel tractor. The 250-kW battery-electric tractor had a larger impact than the system with multiple 50-kW tractors, because of higher material requirement during manufacture and increased energy use due to higher weight. In the electric vehicle scenarios, soil compaction was an increase of 5-12% for the different damage categories, which was lower than for the corresponding diesel scenario.

To accommodate yield loss as an effect of soil compaction, the results were also expressed normalised on the total amount of grain produced during the life cycle, assuming a constant yield based on the 5-year average used in this study (2017-2021). The effects included both the increased fuel use that comes with performing tillage on compacted soil and the reduction in yield levels (Fig. 8). The conventional diesel tractor scenario showed an increase in GWP from 0.039 to 0.057 kg CO_2eq kg_{grain}^{-1} when factoring in soil compaction. This can be compared with

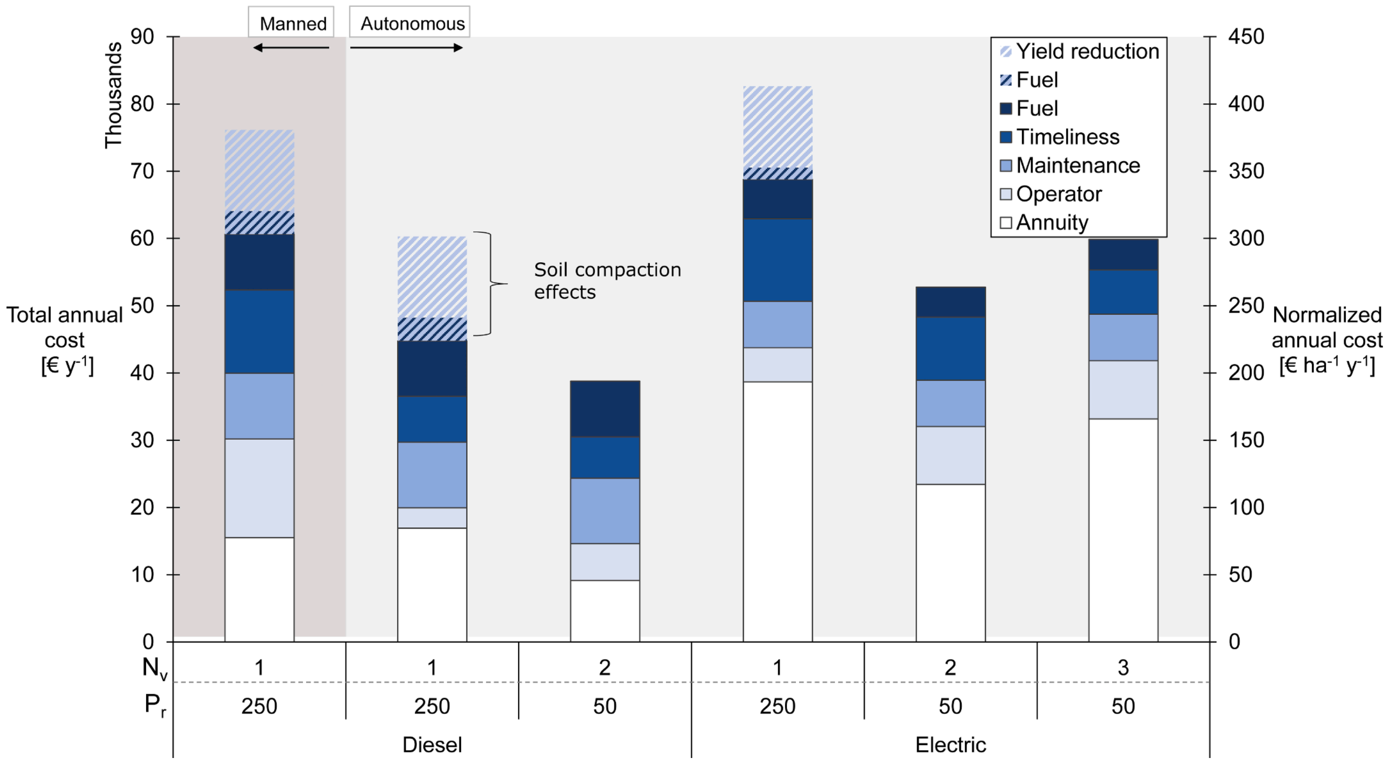

Fig. 6. Total annual cost of the different scenarios, distributed per category of costs (left axis) and normalised to annual cost per hectare (right axis). The annuity is divided over the lifetime of the tractor (generally 15 years) and all other values are 11-year averages (2008-2018). Battery depreciation and replacement are included in the annual cost. Scenarios are differentiated by number of vehicles (N_V), rated power (P_r) and fuel (diesel, electric).

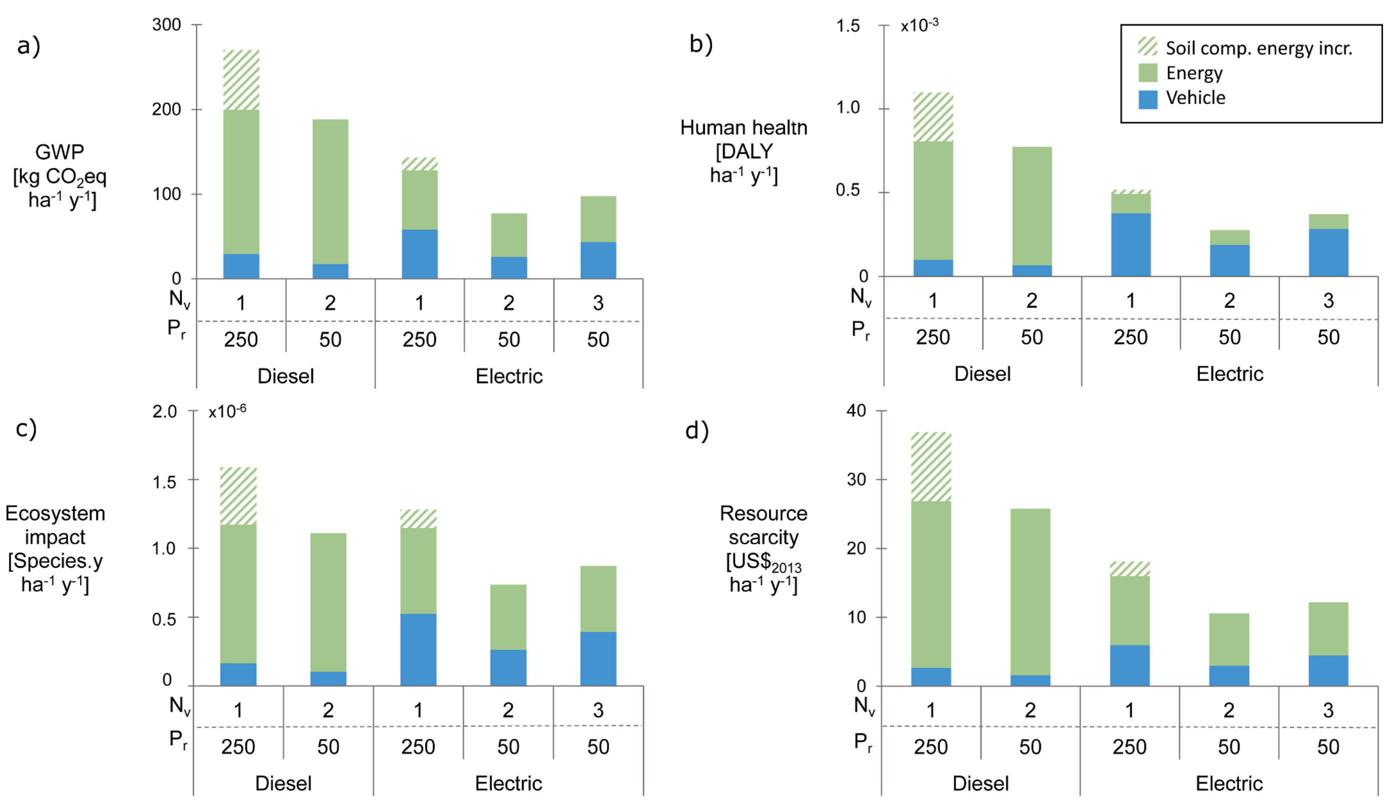

Fig. 7. General life cycle assessment (LCA) results for different scenarios, showing (a) the midpoint characterisation factor global warming potential (GWP) and the damage categories (b) human health, (c) ecosystem impact and (d) resource scarcity. Scenarios are differentiated by number of vehicles (N_V), rated power (P_r) and fuel (diesel, electric). The fuel use increase due to soil compaction (green diagonal stripes) was calculated from values in Lindgren et al. [38]. End-of-life is included in the "Vehicle" category.

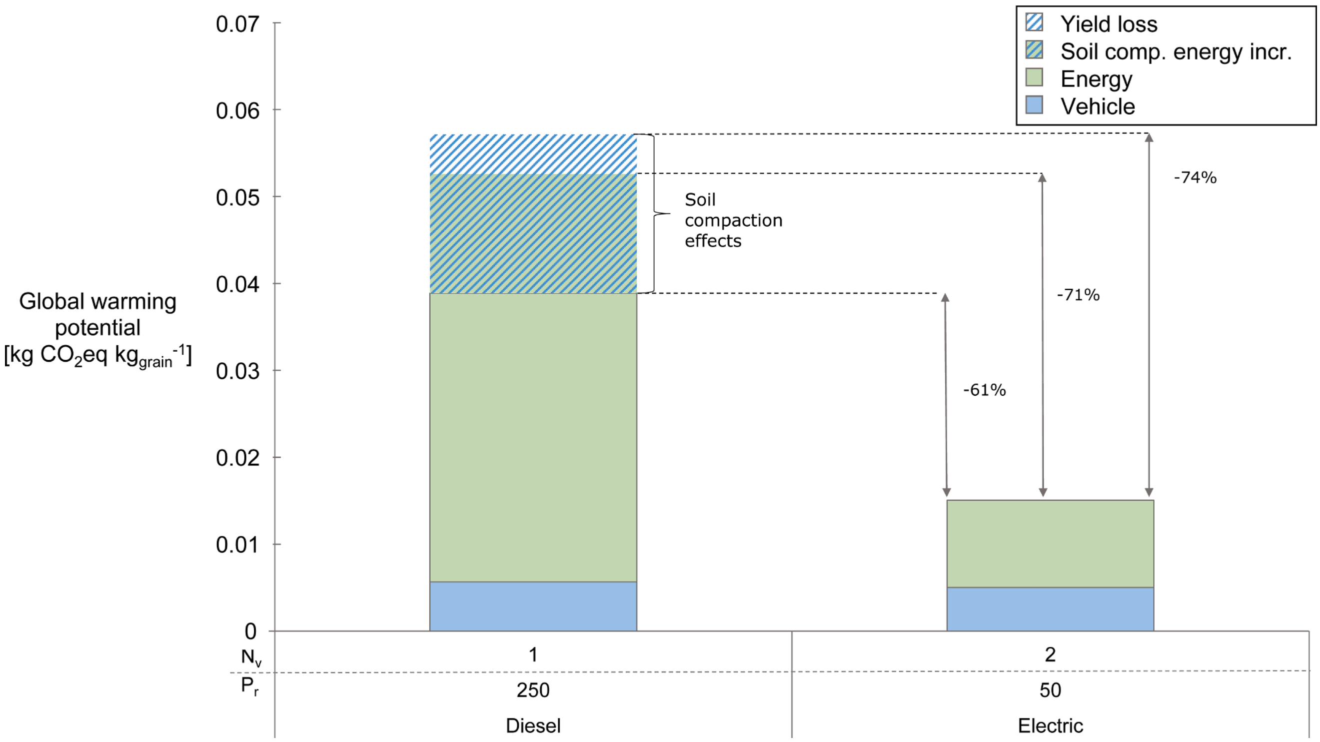

Fig. 8. Life cycle assessment (LCA) results normalised on weight of harvested grain, based on prediction of constant yield at the 5-year average for Sweden (2017-2021). Global warming potential (GWP) reductions compared with the diesel-based scenario are indicated by arrows. Scenarios are differentiated by number of vehicles (N_V) and rated power (P_r).

0.015 kg CO_2eq kg_{grain}^{-1} for the electric tractor scenario.

3.4. Sensitivity analysis

The result of the sensitivity analysis are shown in Table 4. Multiple factors contributed on similar levels to the annual costs, with vehicle lifetime and operator cost both making relevant contributions. Factors connected to soil compaction had a noticeable, but not major, impact. The direct increase from a +10% yield level change was +2% of the total costs, or 1209 € y^{-1}. The indirect changes can be seen in the energy use, where fuel showed higher sensitivity for the diesel scenario than the electric scenario while being on the same level as other factors.

The factor with the highest impact on GWP when changes were simulated was fuel energy use, where a change of +10% in fuel energy use or fuel energy impact resulted in a GWP increase of +7% for the electric tractor scenario and +9% for the diesel scenario. As this was an indirect effect of soil compaction, it is relevant and had a higher impact than other factors considered relevant in electric machine analysis, such

Table 4
Results of one-at-a-time parameter change sensitivity analysis of scenario costs and global warming potential (GWP). The electric scenario refers to a system with two autonomous 50-kW electric vehicles, while the diesel scenario refers to a system with one manned 250-kW diesel-powered vehicle.

		Base value $P(V_0)$	Absolute change Δ_V		Absolute sensitivity S_A		Relative sensitivity S_R	
	Parameter change		**-10%**	**+10%**	**-10%**	**+10%**	**-10%**	**+10%**
Annual cost	*[€ y^{-1}]*							
Electric	Operator time	51,599	-859	858	-2%	2%	0.17	0.17
	Battery cost	51,599	-500	498	-1%	1%	0.10	0.10
	Energy use	51,599	-446	445	-1%	1%	0.09	0.09
	Electricity price	51,599	-446	445	-1%	1%	0.09	0.09
	Vehicle lifetime	51,599	1778	-1457	3%	-3%	-0.34	-0.28
Diesel	Operator time*	80,425	-1468	1469	-2%	2%	0.18	0.18
	Yield loss level	80,425	-1208	1209	-2%	2%	0.15	0.15
	Energy use	80,425	-1514	1515	-2%	2%	0.19	0.19
	Diesel price	80,425	-1514	1515	-2%	2%	0.19	0.19
	Vehicle lifetime	80,425	1282	-1049	2%	-1%	-0.16	-0.13
GWP	*[kg CO_2eq ha^{-1} y^{-1}]*							
Electric	Electricity use/impact	77.3	-5.2	5.1	-7%	7%	0.67	0.67
	Battery impact	77.3	-2.1	2.1	-3%	3%	0.27	0.27
	Vehicle production impact	77.3	-2.6	2.6	-3%	3%	0.3	0.3
	Recycling level	77.3	0.4	-0.5	1%	-1%	-0.06	-0.06
	Vehicle lifetime	77.3	2.9	-2.3	4%	-3%	-0.37	-0.30
Diesel	Diesel use/impact	269.9	-24.0	24.1	-9%	9%	0.89	0.89
	Total vehicle production impact	269.9	-2.9	2.9	-1%	1%	0.11	0.11
	Vehicle lifetime	269.9	3.2	-2.7	1%	-1%	-0.12	-0.10
	Yield loss level [kg CO_2eq kg_{grain}^{-1}]	5.7×10^{-2}	-4.9×10^{-4}	5.0×10^{-4}	-1%	1%	0.09	0.09

as vehicle production, battery impact and fuel price.

To measure sensitivity to changes in hydraulic conductivity, a simulation was performed using a range of values found in the literature and trafficability (when it is “safe” to work on the field) was assessed for ploughing and general tillage with a manned 250-kW diesel tractor. The total time required, a nominal indicator of performance, was also assessed for an autonomous diesel vehicle, to ensure that field status was the only restricting factor. The results indicated a fairly small impact on trafficability at Ksat levels above 2.5 mm m-1 (Fig. 9).

4. Discussion

4.1. Goal, aim, scope

Tillage machine systems of different sizes and with different fuels were simulated and analysed in this study, with specific focus on the effects of soil compaction during tillage. Previous studies of similar systems have focused on performance [25], economics [9] and environmental effects [11]. Improved soil health has been suggested as a beneficial side-effect of the reduced vehicle weight possible with self-driving vehicles, but has rarely been the main focus of studies. This is despite one of the EU biodiversity goals for the New Green Deal being healthy soils through preserving land resources and addressing soil degradation on an international scale [58]. Therefore studies quantifying the potential benefits of systems allowing reduced vehicle weight are relevant.

A choice was made in this study to perform several kinds of analysis in parallel, in order to get a broader understanding of effects, benefits and challenges. When performing analysis on technological systems such as machinery, some choices can optimise one of the goal parameters by omitting others, e.g. an economically beneficial choice can have a large negative environmental impact that may be overlooked if the study does not include an environmental analysis. By studying several goal parameters, more complete and accurate analysis is possible and more informed recommendations can be made.

The focus in this study was on the machinery system and on-site effects of soil compaction, which meant excluding some of the effects of soil compaction, such as effects pertaining to fertiliser use, biological effects and N_2O emissions. Although these are doubtlessly impactful, it is difficult to separate them from other field effects, quantify them and allocate them to soil compaction. Soil compaction is a wide and complex area of research, so a decision was made to focus on certain impacts identified as important in the literature, mainly reduced trafficability, yield loss and increased fuel use. However, comparison of the results with literature values was still possible, as discussed later in this section. Another decision was to limit the scope to a specific scenario of cereal farming on clayey soil in Sweden. The effects of soil compaction differ with soil type, and therefore the choice of soil type is impactful. This means that, unlike in some previous studies [2,16,18], the results are limited to a specific scenario rather than generalised for a large region, nation or crop type. They should thus be seen as giving an example of soil compaction dynamics in vehicle systems analysis, and not as a generally applicable rule. The result is also weather dependent, with 11 years of Swedish weather data used for precipitation. The result is therefore spatially dependent.

4.2. Soil compaction

Use of lighter vehicles was the main source of soil compaction avoidance and alleviation analysed in this study. The main solutions proposed in the literature are lowering axle pressure, adding additional wheels, using tracks instead of wheels, minimising the number of passes or limiting traffic to predetermined lanes (i.e. controlled traffic farming) [19,43,44]. All of these solutions have been well studied, but all are based on the assumption that tractors need to be large and heavy to give high productivity, which has been proven to be true over history. Batey

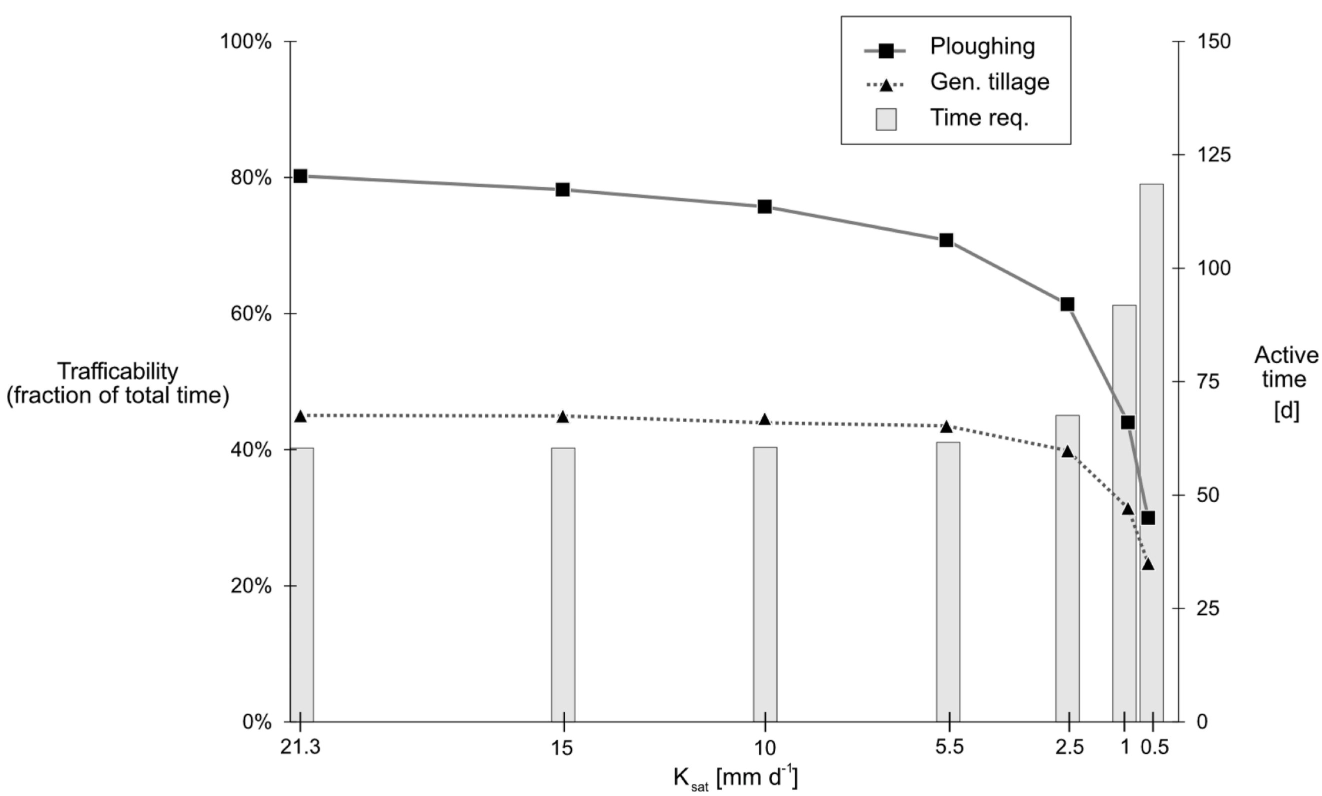

Fig. 9. Simulated trafficability and active time required for a manned 250-kW diesel tractor at different soil saturated hydraulic conductivity (K_{sat}) values. Trafficability (left axis) for ploughing (■) and general tillage (▲) is shown as a fraction of total time during the growing season (machine-independent). Active time required (grey bars, right axis) is also shown for an autonomous 250-kW diesel tractor.

[44] calls the high weight of modern tractors "inevitable and unavoidable", due to current farming economics and practices, as it is the best way to ensure high productivity from a single driver. If lighter vehicles were made more feasible through vehicle autonomy and fuel change, as assumed in this study, that would open up new avenues for soil compaction avoidance.

According to Hamza and Anderson [15], topsoil compaction is related mainly to ground pressure and can therefore be lowered by increasing the tyre-soil contact area using treads or multiple wheels, while subsoil compaction (the focus in this study) is related to the axle load and therefore vehicle weight. An additional important factor is the number of passes, where Hamza and Anderson [15] and Seehusen et al. [59] notes that the first pass cause a major part of the topsoil compaction, but a high number of passes reduces the benefits of lighter vehicles. This is relevant as a lighter vehicle might lead to a higher number of passes, and electric vehicles might increase the traffic on field due to more frequent refuelling. However, this was not included in the study, as the focus was subsoil compaction. Topsoil compaction can have more severe effects on e.g. crop yield than subsoil compaction [21,41] but was outside the scope of this study, which examined long-term differences of a change in machine system. It was assumed that temporary topsoil compaction would still occur, but that it was reversible within a short time for both vehicle systems, while only the heavier vehicle systems would cause irreversible or long-term soil compaction.

A large proportion of arable land is already experiencing soil compaction [18], so data on yield levels and vehicle energy use already implicitly include losses from soil compaction, preventing comparison to a vehicle system with no soil compaction effects. This makes comparison difficult. Keller et al. [2] argue that most field trials compare normally compacted soils with experimentally compacted soils, since most agriculturally managed soils are at least partly compacted. Therefore yield penalties identified in the literature derive from further compaction of already compacted soil and not compaction of uncompacted soil [2]. For ease of presentation and for comparison with literature data, this study made the same assumption and used normally compacted soil as the baseline, with the term heavily compacted soil used for further negative soil compaction by heavy vehicles. This was done because the soil compaction resulting from normal agricultural traffic is hard to avoid, while further soil compaction might be alleviated by different vehicle or management choices.

The level of yield loss due to soil compaction was shown to have a relevant impact on system costs and environmental impact in this study. The literature reports a range of values for yield losses due to soil compaction, most often 4-10% but sometimes losses of 15-16% [16,19]. Graves et al. [18] proposed a value of 4-5% yield loss on British arable land due to soil compaction, which is close to values for Swedish arable land in Parvin et al. [60]. For long-term soil compaction on Swedish soil, Keller et al. [2] reported a yield loss of 8% on clay-rich soil (clay content $>$ 40%), and 6% as a Swedish average. Sonderegger et al. [22] found similar results for soil worldwide, with a 5.5% yearly yield loss for small machines, 8.0% for medium and 9.3% for large. Many factors influence the level of yield loss, but there is agreement in the literature that the loss is non-negligible. Values from the literature used in this study were within the range reported in corroborating sources (Table 3). Thus the 4.5% yield reduction reported for general or light soils for winter wheat [2,18,60] matched the monetary value proposed by Graves, et al. [18] of 49.8 € ha^{-1}. The yield reduction levels proposed by Keller et al. [2] for soils with higher clay content showed a higher monetary loss, but were relevant to the present analysis as Swedish arable soils commonly have a high clay content. For all cereal crops apart from winter wheat, the economic loss at 8% yield reduction was relatively close to the value in Graves et al. [18] and can assumed to be in line with the literature.

Changes in saturated hydraulic conductivity (K_{sat}) and corresponding effects on field trafficability were studied using values and assumptions made in [17]. It was found that the resulting changes in trafficability effect had a minor impact on the economic and performance indicators studied and were not significant, even at large simulated changes in K_{sat}. Poor trafficability has been identified as a potentially significant problem of soil compaction, along with increased risk of flooding [43,44]. In modelling a constant value of K_{sat} is commonly used, but in field trials K_{sat} has been shown to vary significantly between and within fields, making accurate simulation difficult [61]. Very large decreases in K_{sat} (by a factor of 2-28) have been reported [2], suggesting that our estimate of a roughly four-fold reduction might have been conservative and that larger reductions in K_{sat} might be possible in certain situations. Typical K_{sat} values in literature are varied, with 21.3 mm d^{-1} in Witney [34], 74-108 mm h^{-1} in Keller et al. [17] and 20-200 mm d^{-1} in Horn and Fleige [42]. In addition, Lebert et al. [62] states that K_{sat} <100 mm d^{-1} is one indication of harmful soil compaction. However, for the assumed vehicle weights and cropping system, the chosen value of K_{sat} can be assumed to be realistic, albeit low. . Further simulations indicated that lowered K_{sat} had limited effect on the outcome until the level fell below 2.5 mm d^{-1}, when the impact on trafficability became significant (see Fig. 9). In addition, vehicle capacity in the different scenarios was generally well able to handle some extra delay, and it was assumed that the results were adequate. However, soil compaction caused by operations during non-ideal trafficability (i.e. wet fields) should be included in future studies.

4.3. Economics

The total economic difference between the conventional diesel tractor scenario and the main electric tractor scenario was 112 € ha^{-1} y^{-1} in total and 34 € ha^{-1} y^{-1}, in favour of the electric tractor, when disregarding soil compaction effects (Fig. 6). The self-driving electric tractor scenario was shown to be economically competitive with conventional diesel tractors, and including soil compaction made the difference significant in favour of the electric system. A cost comparison by Gao and Xue [63] on transforming conventional tractors to electric found that the electric tractor had 60% of the life cycle cost of the conventional tractor, compared with 71% in this study. An analysis of conventional tractors against autonomous electric tractors by Lampridi et al. [10] produced results favouring the conventional system, but on reducing the recharging times and operator time to values closer to those assumed in this study, the difference between the scenarios was reduced and favoured the electric tractor system in some cases. Lampridi et al. [10] concluded that the high number of assumptions and uncertain estimations make it difficult, although not impossible, to draw conclusions from cost comparisons between field machinery systems. The lowest cost was found to be the lighter, autonomous diesel tractors at 196 € ha^{-1} y^{-1}, as they avoided the negatives of soil compaction as well as the heavy investments of the electric systems, showing how soil compaction alleviation and vehicular autonomy can be economically competitive independent of the electric driveline.

The soil compaction cost for the 250-kW diesel tractor scenario was 78 € ha^{-1}, with 78% from yield loss and 22% from increased fuel use (Fig. 6). Similarly, in Graves et al. [18] the on-site cost of soil compaction was found to be 62.3 € ha^{-1} y^{-1} (adjusted for inflation), with diesel use constituting 8% (5 € ha^{-1} y^{-1}), fertiliser losses 12% and crop productivity losses 80%. Chamen et al. [19] estimated that the increase in gross margin for winter wheat was 78 £ ha^{-1} (91 € ha^{-1}) on reducing ground pressure (an effect of reduced weight) and 117 £ ha^{-1} (136 € ha^{-1}) on introducing controlled traffic farming. Both values are reasonably close to those in this study, although the distribution of costs varied slightly and fertiliser losses were not calculated. This supports the hypothesis that lower vehicle weight leads to improved economic performance. Graves et al. [18] divided the cost of soil compaction into on-site cost (40%) and off-site cost (60%). Parvin et al. [64] also suggested that the majority of the soil compaction cost was from off-site effects. The effects determined in this study were mainly on-site costs, as they related more directly to the scope of the study, and were found to comprise 80% crop productivity losses, 12% fertiliser losses and 8%

additional fuel use. The fuel used increased cost by 29-30%, which is higher than the 8% presented in Graves et al. [18]. Reasons for this include the omission of fertiliser losses and the clay-rich soil used in this simulation compared with the range of British soil types (including peat soils) investigated by Graves et al. [18], where peat was found increase energy use by only 29%, compared with 87% on clay soils.

An assumption was made in the economical calculation that apart from the machinery costs specifically stated; many factors (housing, insurance, implement, harvest and inputs among others) were assumed similar in cost between the scenarios and not explored in detail [9]. It was assumed that in every scenario the machine was a new acquisition, which would have extended to the implements. In reality, implements can often be re-used and switching machine sizes leads to a need to acquire new implements. According to Maskinkalkylgruppen [65], it is in general cheaper to rent or buy two implements for 50 kW tractors than one implement for a 250 kW tractor. New implements for two 50 kW tractors would total 50-75 € ha^{-1} [65] with no extra cost to the conventional tractor system, if implement re-use is assumed. With this cost included, the 50 kw electric tractor system remains economically competitive.

A highly significant assumption in this study was that a manned tractor can be replaced with several smaller autonomous machines. Recent developments justify this assumption [24,66,67] and cost reductions in cereal production of 19-24% have been reported [10,24], compared with a 38% reduction in this study. However, there is still much uncertainty regarding the level of manual oversight such a system requires and who the overseer will be. The rate of oversight and the operator cost have been shown to have a strong effect on the annual cost [9,10]. In this study, based on Lagnelöv et al. [9], it was assumed that an autonomous system would need oversight during 10% of charging/-refuelling, 20% of fieldwork and 30% of road transport, with the service paid per hour. Lowenberg-DeBoer et al. [24] assumed a 10% oversight rate performed by a full time employee who also had other tasks on the farm, with the option of hiring extra labour on a per-hour basis. Lampridi, et al. [10] assumed full oversight, but with 50% labour cost. A preferred method has not been established, so future research must remain flexible in deciding management strategies and cost assumptions for autonomous agricultural vehicles.

4.4. LCA

A number of LCAs have been performed on cereal production, but it was difficult to find studies using similar system boundaries as this study, i.e. mainly focusing on machinery use. Literature values for Swedish wheat production indicate an environmental impact of 0.22-0.70 CO_2eq kg_{grain}^{-1} [68–70], with 0.63 CO_2eq per kg proposed by Moberg et al. [69] as an average value for cereals. In several studies, the machinery system and energy use have been found to contribute around 5-20% of the total GWP impact in grain production [69–72]. This represents a range of 0.011-0.14 kg CO_2eq kg_{grain}^{-1}, with an average value of 0.063 kg CO_2eq kg_{grain}^{-1}. This is close to the GWP of 0.057 kg CO_2eq kg_{grain}^{-1} found in LCA in the present study (Fig. 8).

In addition, Moberg et al. [69] report a value of 0.07 kg CO_2eq kg_{grain}^{-1} for vehicle production and use. For a system with similar system boundaries in this study, GWP was 0.057 kg CO_2eq kg_{grain}^{-1} of which 0.018 kg CO_2eq kg_{grain}^{-1} resulted from soil compaction. This can be compared to the 0.015 kg CO_2eq kg_{grain}^{-1} for the electric tractor scenario. Lovarelli and Bacenetti [73] report values of 190-205 kg CO_2eq ha^{-1} for grain production, compared with 269 kg CO_2eq ha^{-1} in this study (200 kg CO_2eq ha^{-1} on normally compacted soil) (Fig. 7). Since fuel energy was the main contributor to the environmental impact for GWP and for the three damage categories considered, validating fuel consumption is an indirect way to validate the LCA results. Fuel use for the diesel case was 54 L ha^{-1} for normally compacted soil and 76 L ha^{-1} for heavily compacted soils, which are realistic findings compared to literature values of 44-60 L ha^{-1} [36–38] and 66-72 L ha^{-1} for Swedish cereal crops [74]. This indicates that the results in this study linking lower vehicle weight to reduced environmental impact are reasonable. The electric tractor scenario showed potential for significantly lower GWP than previously established.

4.5. Further research & recommendations

Some factors shown to be impactful in previous agricultural LCAs of cereal production were outside the scope of this study. These include N_2O emissions, land use, fertiliser and pesticide use, grain transport and grain drying. Some soil compaction effects were also outside the scope of the study, but the results confirmed the importance of including soil compaction in environmental impact analysis and LCAs [13,21]. In fact, the results indicated that a noticeable impact of soil compaction on all environmental impact categories studied (GWP, human health, ecosystem impacts and resource scarcity).

In further research, we recommend including soil compaction in machinery analyses and assessments. If lighter vehicles emerge as a probable technology pathway due to autonomy, the recommended mitigation and avoidance measures listed in the literature need to be re-evaluated. Furthermore, the soil compaction factors omitted in this study should be included in future work on the economic and environmental effects of soil compaction and machinery systems, and in LCAs of grain production.

5. Conclusion

Electric, autonomous tractors makes it possible to replace one heavy machine with several lighter while being economically viable and avoiding further soil compaction. Soil compaction was shown to have economic and environmental impacts, mainly through increased fuel energy use and yield losses. Decreased hydraulic conductivity due to soil compaction had a minor effect on performance and economics and no effect on environmental impact in the scenarios studied.

The economic impacts of soil compaction were non-negligible, increasing the costs by 20% on heavily compacted soil. The environmental impacts were also non-negligible, with soil compaction increasing climate change per kg grain by 46% compared with normal soil compaction. The increase in climate change impact was 26% when calculated per hectare (which disregarded yield loss). The increase was roughly similar (26-27%) for the three damage categories studied (human health, ecosystem impact and resource scarcity). This was mainly attributable to diesel use, which is already a large factor in the environmental impact of agricultural machinery use, and increased energy need from soil compaction, which further increased this impact.

The economic and environmental impacts of further soil compaction were similar in magnitude to those of making tractors autonomous. Overall, soil compaction gave rise to some of the largest impacts in machinery analysis, showing that it should be considered in machinery analysis and calculations.

Compared with a conventional scenario with a heavy diesel tractor and associated soil compaction, electric autonomous tractors with lower vehicle weight reduced operational costs by 29-33%, climate impact by 71-73% and damage category impacts by 54-75%. Soil compaction avoidance alone might not provide a strong enough incentive for a shift to electricity or autonomy but, as an added benefit among others, it provides a strong argument for a technology shift from heavy diesel tractors to lighter, self-driving electric tractors. Soil compaction further amplifies existing trends and including avoided soil compaction in system analysis maximises profitable and environmentally beneficial choices and minimises detrimental choices.

Funding

This work was supported by the Swedish Government research program “STandUP for Energy” and by the Swedish Energy Agency (grant number P44831-1).

CRediT authorship contribution statement

Oscar Lagnelöv: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Gunnar Larsson:** Conceptualization, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Anders Larsolle:** Conceptualization, Validation, Writing – original draft, Supervision. **Per-Anders Hansson:** Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

We thank STandUP for Energy and The Swedish Energy Agency for funding this research.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.atech.2022.100156.

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