INTRODUCTION

Over the last decades, the industrialization and intensification of agriculture have intensely changed arable farming (Bochtis & Sørensen, 2014). The machinery operating in the fields are increasing their capacity as a response to the necessity of producing more with lower unit production costs. This higher capacity inevitably comes with higher weight, which can result in long-term subsoil compaction problems (Keller et al., 2019; Schjønning et al., 2015). This world-wide tendency is leading to poorer physical soil properties due to compaction within many arable fields that also has negative effects on crops, for example, limiting the development of the roots (Bengough et al., 2011; Lipiec et al., 2012), affecting negatively the mineralization of...
soil organic carbon and nitrogen (Neve & Hofman, 2000), and eventually cause yield decrease (Alblas et al., 1994; Chen & Weil, 2011; Lipiec & Hatano, 2003; Obour et al., 2019a, 2019b; Schjønning et al., 2016; Tim Chamen et al., 2015), as well as the need for increased energy input in tilling compacted soils due to higher penetration resistance (Schjønning et al., 2016; Tim Chamen et al., 2015). Apart from these negative effects, soil compaction has negative consequences on the environment too in terms of, for example, increased risk of nitrogen leaching, nitrous oxide emissions (Tim Chamen et al., 2015; Vermeulen & Mosquera, 2009) or increased risk of erosion (Bogunovic et al., 2018; Braunack & Dexter, 1989). In addition to heavy loads, the intensity of traffic in the field is also a major cause to soil compaction problems (Arvidsson & Håkansson, 1991; Håkansson & Reeder, 1994; Hamza & Anderson, 2005; Keller et al., 2004; Seehusen et al., 2019). Traffic intensity is also in literature often referred to as wheeling intensity. Traffic intensity has been defined as the product of the weight of a machine and the distance driven per hectare (Arvidsson & Håkansson, 1991). Even if the first wheeling is considered most harmful (Bakker & Davis, 1995), repeated traffic causes additional stress and leads to accumulative plastic deformation (Bakker & Davis, 1995; Balbuena et al., 2000; Horn et al., 2003; Pulido-moncada et al., 2019; Schjønning et al., 2016). Repeated wheeling with lighter loads may even result in more harmful effects than a single heavy-loaded pass (Schjønning et al., 2016; Seehusen et al., 2019). The problems associated with soil and subsoil compaction evidence the need for mitigation strategies caused by heavy and reiterative traffic in the field.

Various soil compaction mitigation strategies have been described in literature in regards to equipment, soil management, crops and field operations (Alakukku et al., 2003; Batey, 2009; Chamen et al., 2003; Hamza & Anderson, 2005; Keller & Arvidsson, 2004; Tim Chamen et al., 2015). Equipment solutions to mitigate compaction are on-land ploughing (Munkholm et al., 2005), deep ripping (Schneider et al., 2017), reduced wheel load by the use of tandem wheels, tandem axles and regulation of tyre inflation pressure (Keller & Arvidsson, 2004; Tim Chamen et al., 2015). Soil management practices to limit soil compaction includes modelling soil readiness for assisting farm managers in scheduling when to operate in their fields (Edwards et al., 2016; Obour et al., 2019a, 2019b), and the use of well-designed drainage systems to reduce the water content and consequently increase the trafficability of the soil (Chamen et al., 2003). Cover crops have also been found to be able to improve soil hydraulic properties and thereby reduce soil compaction problems (Çerçioğlu et al., 2019). Finally, preventive field management practices can include controlled traffic farming (Gasso et al., 2013; McHugh et al., 2009), or no-tillage (Renato Nunes et al., 2018). In addition, reducing traffic intensity in heavy-loaded operations, such as harvesting, by the use of infield optimized route planning (ORP) has been pointed out as a solution to reduce soil compaction problems (Bochtis et al., 2012; Edwards et al., 2017; Gorter, 2019). Bochtis et al. (2012) presented a decision support system (DSS) that used soil physical and chemical properties to estimate the potential risk of soil compaction and accordingly optimize the route of slurry application. The system was tested in one field and was able to reduce the risk factor by 61% compared to recorded data. Gorter (2019) presented an ORP method for capacitated harvesting operations that takes into account weight variations and soil compaction susceptibility based on infield wet areas. The method was tested in three fields and optimized the path of the grain cart according to its weight and the field areas more vulnerable to soil compaction. While the DSSs presented by Bochtis et al. (2012) and (Gorter, 2019) optimize in regards to soil compaction reduction and require field data collection prior to the operation to estimate the potential risk, the system employed in Edwards et al., (2017) reduced the travelled distance by the use of an ORP tool in neutral material flow operations, which reduced traffic intensity, especially in the headland area.

In this paper, a harvest logistics fleet optimization tool, that is, an ORP tool for harvesting operations (Villa-Henriksen et al., 2018), was used to evaluate the effectiveness of ORP to reduce repeated traffic, heavy loads and accumulated traffic load, and thus the risk of soil compaction. The harvest fleet logistics system coordinate plans and optimises the route of all vehicles, so that the overall harvest time is minimized, as well as the travelled infield distance is reduced. The ORP system does not require field data collection before the operation and addresses coupled operations with more than one vehicle carrying loads with varying weights, differing from Edwards et al., (2017) which only involves one vehicle with a constant weight.

It is hypothesized that ORP can reduce the infield traffic, and consequently ORP can be employed as a complementary soil compaction mitigation strategy in arable farming.

**2 MATERIAL AND METHODS**

An ORP tool for harvest operations (Villa-Henriksen et al., 2018) was employed for optimizing the operation in a set of recorded fields. The fields belonged to Lisbjergråd, a commercial farm located around Havndal in Jutland, Denmark (56.6530°N, 10.197475°E), which fields were harvested between the 8th and 14th of August of 2017. The position of all vehicles involved was recorded using GNSS loggers QSTARZ Travel Recorder XT, which use GPS satellites with a frequency of 1 Hz. In total six fields were fully recorded for the evaluation (Figure 1). The fields varied in size (2–21 ha) and shape and may be considered typical for Danish arable fields (Caspersen & Andersen, 2016; Enemark & Sørensen, 2016). Data from more fields were also recorded.
but had to be discarded because they either were incomplete or partially harvested at different times making them incomparable to the optimized solution.

The logged field harvest operations were analysed with the aim of having the same parameters in the computer optimized solution as in the recorded operations (Table 1). The total yield per field was calculated based on the CAN bus grain flow data from the harvester. The harvester was calibrated for a bulk density of the crop of 0.56 kg m$^{-3}$, which was used to estimate grain levels in harvester tank and grain carts. The vehicle speed parameters used in the simulations were 1.2 m s$^{-1}$ for working speed, that is, speed during harvesting, and 1.9 m s$^{-1}$ for non-working speeds.

The ORP tool employed for the harvest operations coordinate plans and optimises the route of harvester and grain carts, so that the overall harvest time is optimized, as well as the travelled distance is minimized. The system ensures the grain carts will receive the loads at the right time and at the right spot. The harvesting of the set of fields was computer simulated with the input parameters registered (Table 1). The harvester weight was 28,982 kg, and the grain cart weight including the tractor was 16,320 kg. The app-based version of the ORP fleet harvest tool has been described in Villa-Henriksen et al. (2018).

The position data for the recorded operations were processed before the evaluation analysis by removing all data points placed outside of the field polygon boundaries as well as points outside of the time range in which the fields were harvested. It was observed during the analysis that Field A lacked data points from the grain cart due to issues in the setup of the GPS logger. In order to calculate the traffic of Field A, the missing position data were estimated by interpolation adding one data point per missing timestamp in a straight line within the existing adjacent data points.

For the evaluation, the fields were divided into a grid where the gridline spacing was equal to the working width of the harvester, that is, 12 m, and the orientation of the grid followed the angle of the working direction in the main

**TABLE 1** Parameters used in the computer simulations for each of the fields

<table>
<thead>
<tr>
<th>Field ID</th>
<th>Size (ha)</th>
<th>No. headlands</th>
<th>Total crop output (Mg)</th>
<th>Working width (m)</th>
<th>Harvester Tank volume (m$^3$)</th>
<th>No. trailers</th>
<th>Volume (m$^3$)</th>
<th>Time out of field (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>21</td>
<td>3</td>
<td>82.54</td>
<td>12</td>
<td>14.5</td>
<td>1</td>
<td>31</td>
<td>1,367</td>
</tr>
<tr>
<td>B</td>
<td>9.4</td>
<td>2</td>
<td>39.14</td>
<td>12</td>
<td>14.5</td>
<td>1</td>
<td>26</td>
<td>1,025</td>
</tr>
<tr>
<td>C</td>
<td>1.6</td>
<td>2</td>
<td>6.61</td>
<td>12</td>
<td>14.5</td>
<td>1</td>
<td>26</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>3.1</td>
<td>2</td>
<td>10.72</td>
<td>12</td>
<td>14.5</td>
<td>1</td>
<td>26</td>
<td>0</td>
</tr>
<tr>
<td>E</td>
<td>2</td>
<td>2</td>
<td>6.02</td>
<td>12</td>
<td>14.5</td>
<td>1</td>
<td>26</td>
<td>0</td>
</tr>
<tr>
<td>F</td>
<td>12.7</td>
<td>3</td>
<td>51.65</td>
<td>12</td>
<td>14.5</td>
<td>1</td>
<td>26</td>
<td>931</td>
</tr>
</tbody>
</table>
part of the field. For each of the grid cells, three variables were measured, that is, traffic occurrences, accumulated traffic load per grid cell and maximum traffic load per grid cell. Traffic occurrences refer to the number of times any vehicle has driven on a grid cell and accounts for repeated traffic. Accumulated traffic load per grid cell represents the sum of the weights of vehicles passing the grid cell including the harvested grain in their tank or grain cart. Finally, the maximum traffic load per grid cell expressed the heaviest vehicle including grain content that has passed over the grid cell. This last variable was analysed in order to address the possible effects on load from using ORP. The traffic occurrences distributed across field grid cells were displayed in map form and in bar chart of the percentage of trafficked grid cells.

For each of the fields the total sum, the mean and standard deviations, the median, as well as the maximum values for each of the three variables were calculated. Additionally, the relative difference (Equation 1) for each field and variable was also calculated, that is, the difference between recorded \( (x_r) \) and simulated \( (x_s) \) total traffic occurrences per field divided by the arithmetic mean.

\[
\text{Relative difference } (x_r, x_s) = \frac{x_r - x_s}{x} \tag{1}
\]

Finally, the field size weighted arithmetic mean of the relative differences for each of the variables were calculated. The field size was based on the number of grid cells attributed to each field.

The harvesting times for the ORP tool and recorded operations are not included in this study because they do not affect the traffic variables studied and would require a thorough analysis of recorded speeds and accelerations as well as to include them cautiously in the simulation to achieve an equitable comparison, which is not in the scope of the article.

The correlation between the accumulated traffic load and traffic occurrences was also studied to observe its dependency in order to address the possibility of estimating accumulated weight based only on traffic occurrences. The correlation analysis was divided into the two different grain cart volumes employed in the harvest operations, that is, 31 m\(^{-3}\) used in Field A, and 26 m\(^{-3}\) in the rest of fields (Table 1).

The processing and analysis were performed using targeted code in Java and Python programming languages and the spatial data was visualized employing QGIS v. 2.14.

### 3 | RESULTS

The harvest logistics tool reduced the total number of traffic occurrences per grid cell in the set of fields with a field size weighted mean of the relative differences of 9.8%, or
12.9% when Field F is excluded. The relative difference of total traffic occurrences ranged from 0.7% to 50.5%. The median of the simulated harvest was reduced from 2 to 1 traffic occurrence per grid cell in all fields, excluding Field E and F where it was equal. The results for maximum traffic load per grid cell were higher for all fields for the ORP tool with a field size weighted mean of relative differences of −4.0%, and the relative differences ranging from −1.9% to −5.1%. The results for the ORP tool for the accumulated traffic load per grid cell were reduced in 5 of the fields and increased in one of them, having a field size weighted mean of relative differences of 5.6%, and the relative difference ranging from −4.3% to 39.8%. The medians of the accumulated weight per grid cell were importantly reduced in Fields A, B, C and D, while for Fields E and F was slightly higher. The complete results for traffic occurrences (Table 2), maximum traffic load per grid cell (Table 3) and accumulated traffic load (Table 4) are collected each in a dedicated table. A bar chart for each field with the distribution of traffic occurrences for the recorded and simulated data is shown in Figure 3. In the figure, it is observed that the simulated data tends to be more positively skewed than the recorded data, meaning that there were more grid cells being travelled on one or two times and less with higher traffic occurrences. The percentage of grid cells with more than one traffic occurrence was reduced in all but two fields, that is, Field E and Field F. The field traffic maps for recorded and simulated data are presented in Figure 2, where it is visualized in colour-scale the lighter and heavier trafficked areas.

The results indicate a high correlation between the accumulated traffic load and traffic occurrences for both grain cart volumes employed in the harvest (Figure 4). The coefficient of determination \( R^2 \) for the bigger grain cart was 0.994 for the recorded field and 0.988 for the simulated field. The coefficient of determination for the smaller grain cart 0.983 for the recorded field and 0.986 for the simulated fields.

### Table 3 Maximum traffic load (Mg)

<table>
<thead>
<tr>
<th>Field</th>
<th>Recorded</th>
<th>Simulated</th>
<th>Relative difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area (ha)</td>
<td>Grid cells</td>
<td>Total</td>
</tr>
<tr>
<td>ID</td>
<td></td>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>21</td>
<td>1501</td>
<td>47,432.3</td>
</tr>
<tr>
<td>B</td>
<td>9.4</td>
<td>685</td>
<td>21,653.5</td>
</tr>
<tr>
<td>C</td>
<td>1.6</td>
<td>115</td>
<td>3,488.1</td>
</tr>
<tr>
<td>D</td>
<td>3.1</td>
<td>227</td>
<td>7,065.1</td>
</tr>
<tr>
<td>E</td>
<td>2</td>
<td>152</td>
<td>4,800.3</td>
</tr>
<tr>
<td>F</td>
<td>12.7</td>
<td>879</td>
<td>27,677.7</td>
</tr>
</tbody>
</table>

Field size weighted arithmetic mean −4.0
field F is excluded, the traffic occurrences would be reduced by a field size weighted mean of the relative differences of 12.9% when employing the ORP tool.

The ORP tool performed particularly well in Field C and Field D (Table 2 and Figure 3), which had very small field areas, with relative differences of 50.5% and 42.5% respectively. In these fields, as well as in Field E, the total yield output was smaller than the grain cart size, implying that the harvester had to empty its grain tank two times at most (Table 1). The recorded data shows that the grain carts travelled unnecessary distances as they did not know how to drive strategically in the field to meet the harvester at the right time and place, resulting in additional traffic. In the simulated operation, the grain carts minimized their traffic by waiting by the gate until they timely drove to receive an unload. This characteristic of the ORP tool reduces significantly the traffic occurrences produced by the grain carts, and in general the overall infield traffic in harvest operations. Considering that the harvester has to traverse the whole field, that is, at least one time per grid cell, a field size weighted mean of relative differences of 9.8% is an important reduction, especially taking into consideration the median values for the simulated data (Table 2), in which four of them were reduced from 2 to 1 traffic occurrences per grid cell.

The percentage of grid cells with repeated traffic, that is, with more than one traffic occurrence, is important for evaluating the effectiveness of an ORP tool to reduce repeated traffic. The simulated harvest was able to reduce repeated traffic in four of the six fields (Figure 3). The reduction was especially important in Field C and D and did not occur for Field E and F. In the recorded data, all the fields excluding Field E had repeated traffic in more than 50% of the grid cells, meaning that more than half of the field surface is prone to experience the negative consequences of repeated traffic. Any reduction in the percentage of grid cells with repeated traffic will avoid its negative effects in those parts of the field. The simulated data had repeated traffic in less than 50% of the grid cells in five of the six fields. Even though Fields E and F had overall traffic reduced (Table 2), they had more repeated traffic than the recorded data (Figure 3). In Field F this was caused by the orientation of the rows in relation to the obstacle in the middle of the field, as previously discussed. In Field E it was caused by the optimization calculating an unloading point at the opposite edge of the field in regards to the gate, obliging the grain cart to drive a longer path than in the recorded data. As the ORP tool aims at reducing the overall operational time, this issue may occur in some smaller fields with one infield unload.

In the set of fields studied, field size does not have a relation to repeated traffic reduction, as the unpredictable human factor has very much influence on the traffic in the recorded fields. With a larger dataset it would be expected to have in average a higher reduction for larger fields, than for smaller. This is mainly because the ORP tool reduces ineffective travelled distances by the grain carts and the number of unloads is minimized, thus having more effect in the reduction of repeated traffic. Field shape may also influence the reduction of repeated traffic as more complex fields can become more challenging for the operators to drive optimally, so the ORP tool could potentially be more effective. However, in some cases the ORP tool may optimize harvest time reduction in a way that does not benefit traffic reduction, for example, in the case of Field F. Larger datasets would be required to analyse the relation between traffic and field size and shape, as well as the capability of an ORP tool to reduce traffic in any type of field.

The results indicate a high correlation between the accumulated traffic load and traffic occurrences (Figure 4). The coefficient of determination (R^2) for the bigger and smaller grain carts and for both recorded and simulated harvesting operations rounded 0.99, which shows a very high correlation. Consequently, in this specific case, it also indicates that traffic occurrences do not require weight as a parameter in the calculations in order to predict the traffic occurrences. The cause for this correlation is twofold: the high weight of the harvester, which has to drive over each grid cell of the field, and the relatively small weight differences between full (8 Mg) or empty tanks in regards to the harvester weight (29 Mg). Additionally, as the tractor with a full grain cart sums around 34 Mg, which is very close to the harvester weight with a full load, the relation to traffic occurrences becomes apparent.

<table>
<thead>
<tr>
<th>ID</th>
<th>Area (ha)</th>
<th>Grid cells</th>
<th>Total</th>
<th>Mean per grid cell (SD)</th>
<th>Median</th>
<th>Max</th>
<th>Total</th>
<th>Mean per grid cell (SD)</th>
<th>Median</th>
<th>Max</th>
<th>Relative difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>21</td>
<td>1501</td>
<td>101,516.1</td>
<td>67.6 (60.9)</td>
<td>48.2</td>
<td>431.8</td>
<td>95,406.1</td>
<td>64.3 (45.3)</td>
<td>36.9</td>
<td>430.6</td>
<td>6.2</td>
</tr>
<tr>
<td>B</td>
<td>9.4</td>
<td>685</td>
<td>40,723.3</td>
<td>60.6 (38.5)</td>
<td>53.3</td>
<td>254.5</td>
<td>40,098.4</td>
<td>59.8 (40.4)</td>
<td>36.3</td>
<td>254.8</td>
<td>1.6</td>
</tr>
<tr>
<td>C</td>
<td>1.6</td>
<td>115</td>
<td>7,056.6</td>
<td>61.4 (27.3)</td>
<td>53.1</td>
<td>172.4</td>
<td>4,715.2</td>
<td>41.7 (24.2)</td>
<td>33.0</td>
<td>165.7</td>
<td>39.8</td>
</tr>
<tr>
<td>D</td>
<td>3.1</td>
<td>227</td>
<td>15,265.8</td>
<td>67.3 (39.5)</td>
<td>57.5</td>
<td>229.8</td>
<td>10,938.7</td>
<td>48.4 (31.2)</td>
<td>35.0</td>
<td>228.0</td>
<td>33.0</td>
</tr>
<tr>
<td>E</td>
<td>2</td>
<td>152</td>
<td>7,592.0</td>
<td>50.6 (33.5)</td>
<td>33.9</td>
<td>185.5</td>
<td>7,017.6</td>
<td>46.2 (24.3)</td>
<td>34.7</td>
<td>224.5</td>
<td>7.9</td>
</tr>
<tr>
<td>F</td>
<td>12.7</td>
<td>879</td>
<td>50,734.5</td>
<td>57.7 (36.5)</td>
<td>47.6</td>
<td>261.3</td>
<td>52,967.1</td>
<td>60.7 (35.1)</td>
<td>52.7</td>
<td>252.1</td>
<td>-4.3</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>5.6</td>
</tr>
</tbody>
</table>

**TABLE 4** Accumulated traffic load (Mg)
FIGURE 2  Traffic occurrence maps of the fields studied for the recorded and simulated harvest operations
Heavy load leads to subsoil compaction (Håkansson et al., 1988; Keller et al., 2019). Consequently, the maximum traffic load per grid cell was included in this study. The results show that the maximum traffic load per grid cell was higher for the ORP than for the recorded data, mainly because the ORP model filled the grain cart always to 100%, which was not the case in the recorded data. The results show a field size weighted mean of relative differences of −4.0% for the maximum traffic load per grid cell. This could be caused by yield sensor calibration issues or because the operators had to guess...
on the go when a tank or grain cart was really full. Nonetheless, looking closer to the results, the maximum traffic load per grid cell had mean values around 30–33 Mg with standard deviations of 1–3 Mg (Table 3), and the differences between average recorded and simulated data were in fact in all cases smaller than 2 Mg per vehicle. This suggests that for a given fleet of vehicles for grain harvest, ORP does not significantly increase the risk of soil compaction due to heavy traffic load but significantly reduces repeated traffic as previously stated.

The concept of traffic intensity described by Arvidsson and Håkansson (1991) refers to the product of the weight of a machine and the driven distance per hectare (Mg km⁻¹ ha⁻¹), which includes heavy loads and infield travelled distance in one variable, and can cover a whole season of field operations. The infield travelled distance is related to the repeated traffic. The concept of traffic intensity was employed by Gorter (2019) for estimating the reduction of travelled distances by heavy-loaded machinery in wet areas. In this study, a different approach was chosen, which distinguishes heavy loads from repeated traffic, and has a much finer spatial resolution than a hectare, that is, squares of 12 m sides.

Nonetheless, the method used to calculate traffic occurrences and load may not provide the full picture, as the weight is not equally distributed inside the grid cell. Furthermore, equal traffic loads per grid cell for different vehicles can translate into very different induced stress on the soil. The weight distribution is dependent on the axel load for each wheel along with the contact area of the wheel (Hamza & Anderson, 2005; Keller & Arvidsson, 2004; Seehusen et al., 2019). The axel load is subjected to mechanical design of the vehicle, which can distribute the weight differently between for example front and back wheels. The contact area is dependent on the inflation pressure and the tyre design. Due to most of these parameters were not known during the harvest operations, the focus has been set on traffic occurrences per grid cell, knowing that repeated traffic can be more harmful to soil structure than single wheeling with high load (Seehusen et al., 2019). Modelling tools such as Terranimo (Stettler et al., 2014), FRIDA (Schjønning et al., 2008) as well as other scientific models (e.g. Keller & Arvidsson, 2016) can be employed to simulate and study the wheel stress induced to the soil and the compaction for different soil types and conditions.

4.3 | Accumulated traffic

Even if the first wheeling is considered most harmful, repeated traffic results in accumulated plastic soil deformation.
and compaction (Bakker & Davis, 1995; Horn et al., 2003; Seehusen et al., 2019), with significant yield penalties compared to single-pass traffic (Arvidsson & Håkansson, 1991; Schjønning et al., 2016), and may lead to subsoil compaction with long-term persistence (Balbuena et al., 2000; Håkansson et al., 1988; Pulido-moncada et al., 2019). As in harvesting operations the first wheeling is unavoidable, since the harvester needs to harvest the whole field, the reduction of additional traffic is central in these types of operations. This is particularly relevant when the soil conditions are not ideal. Considering the constrained time frames operators are forced to work on due to weather conditions or farm scheduling limitations, it obliges them to drive under suboptimal soil conditions increasing soil compaction issues (Edwards, 2015; Edwards et al., 2016; Orfanou et al., 2013).

The negative effects of accumulated traffic in soil compaction are not only dependent on the soil conditions, but as discussed earlier, also on the weight distribution and wheel contact area of the different vehicles, which were unknown in this study. Additionally, the differences in axle width, wheel number and distribution, as well as the driving patterns inside a grid cell of the harvester and grain carts make the negative effects in soil compaction of accumulated traffic difficult to estimate.

The accumulated traffic load per grid cell was reduced in most of the fields studied resulting in a field size weighted mean of relative differences of 5.6%. As described previously, the accumulated load per grid cell is directly correlated to the traffic occurrences, which makes the count of traffic occurrences a straightforward concept to account for repeated traffic and could potentially be used for estimating the approximate effects of accumulated traffic load in localized areas.

From the traffic maps (Figure 2) it is clear that the grain carts in the simulated data drove across the field making the shortest connection from or to an unloading event. This happens also sometimes in real life but may not be the ideal situation since the driving direction is not respected in the main field area and is unacceptable in controlled traffic farming.

### 4.4 | Applicability of the ORP tool

Soil compaction induced by vehicle traffic may not be possible to eliminate entirely, but it can be reduced by employing intelligent tools that can manage vehicle traffic (Raper, 2005). ORP besides optimizing the operation in time (Bochtis et al., 2012, 2014; Edwards et al., 2017), it does also reduce vehicle traffic in the set of fields studied in this paper. ORP can be therefore considered a soil mitigation strategy that in combination with other strategies can reduce the degradation of arable soils across the globe. ORP does not require major investments or changes in the machinery fleet of the farm, as it can be without difficulty employed through smart technologies (Villa-Henriksen et al., 2018).

In order to minimize further soil compaction, ORP for capacitated operations can be targeted include the wheel load carrying capacity of the soil in a field in the route planning. In that manner, the vehicles are directed to avoid the wettest areas of a field when carrying heavy loads. ORP that targets minimizing risk for soil compaction have been proposed for slurry application (Bochtis et al., 2012) as well as for root crop harvesting operations (Gorter, 2019). The ORP tool employed in this study does not require any data collection prior to the operation and can reduce the traffic occurrences in the field, but does not consider high-risk areas, which may cause soil compaction problems. Bochtis et al., (2012) altered the driving direction of the operation according to an electrical conductivity map of the field that addressed the risk of soil compaction. The map was generated from field measurements prior to the operation and based on it the ORP system directed the tractor in accordance to its load and the soil risk factor. Gorter (2019) aimed to reduce the distance of heavy-loaded grain carts in fictive wet areas for high yielding root crops based on a capacitated arc routing problem with a Tabu search algorithm. ORP with special attention to soil compaction risk requires previous mapping based on either infield measurements or on modelling tools. In that manner, ORP can significantly reduce soil compaction across the field in general, and specifically in high-risk areas. However, altering the route according to a wheel load carrying capacity map may imply more repeated traffic in certain areas and more distance travelled by the vehicles. Further research should address these issues.

### 5 | CONCLUSION

A harvest logistics fleet optimization system was employed to simulate traffic occurrences for a set of fields as well as compared it to the non-optimized recorded harvest traffic occurrences. The results show that the ORP tool was able to reduce traffic occurrences with a field size weighted mean of relative differences of 9.8% and reducing repeated traffic in four of the six fields studied. The tool performed better in some fields than others, but for all cases, the tool managed to decrease the traffic occurrences. As the tool coordinates the vehicles for timely unloading events, it avoids unnecessary traffic from especially the grain carts, consequently reducing the total traffic in the field. Even though ORP is not directly intended for infield traffic reduction, it can accomplish this task and adds an extra element to the farm strategy for reducing soil compaction. It can be concluded that soil compaction resulting from vehicle traffic can potentially be reduced by the use of optimized route planning, especially when soil conditions are not ideal.
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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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REFERENCES
Gorter, N. (2019). Route optimization of primary and service units in agricultural harvesting operations. Wageningen University and Research Centre. Available at: https://edepot.wur.nl/504244


