COMMENTARY

Projections of yield losses and economic costs following deep wheel-traffic compaction during the 2019 harvest

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Abstract
Economic projections after widespread deep compaction during wet harvests are essentially nonexistent. Therefore, we project state-level economic costs to producers in North Dakota and Minnesota for the upcoming 2020 and 2021 crops. We provide economic cost graphs as functions of grain sell prices and fractions of land impacted by deep wheel-traffic compaction. At corn (Zea mays L.) and soybean [Glycine max (L.) Merr.] sell prices of US$3.06 bu⁻¹ and $8.78 bu⁻¹ for North Dakota and $3.26 bu⁻¹ and $8.98 bu⁻¹ for Minnesota, we estimate a minimum economic cost of US$587 million through 2021, excluding environmental externalities and other feedbacks, for every 10% of lands compacted during the 2019 harvest. Actual impacted land area may range up to 30%, resulting in a range of US$0 to $1.76 billion of actual costs. Precise large-scale, deep-compaction reports/sensing is needed to determine actual fractions of impacted land. Policies incentivizing conservation practices to reduce the occurrence of field traffic on wet soils are strongly encouraged.

1 | HARVEST CONDITIONS IN 2019—NORTH-CENTRAL AND UPPER MIDWEST, USA

After a wet spring and delayed planting in 2019, excessively wet field conditions at harvest caused difficult decisions for many producers throughout the north-central and upper Midwest regions of the United States. This was the reality in 2019 for nearly all corn (Zea mays L.) and soybean [Glycine max (L.) Merr.] producers due to these crops long maturing needs and the region’s brief growing season between winters. Most producers had to choose between (a) harvesting in less-than-ideal field conditions (i.e., high risk for causing ruts and deep soil compaction), (b) delaying harvest until the frozen, snow-covered winter months, or (c) delaying harvest until after spring thaw in 2020.

As a result, numerous fields had damage to soils as evidenced by deep ruts from combines and grain wagons. Soil compaction became a major issue even in fields with delayed harvest to the frozen winter months. As winter progressed into February, producers encountered soft, unfrozen soils in some fields where the ground had already thawed (NDAWN, 2020). The early and consistent snow cover limited the depth of soil freezing, and heat from deeper depths thinned the frozen layer from below.

Deep soil compaction (i.e., below the depth of tillage) caused by wheel traffic is well known to cause yield reductions in subsequent crops. However, the persistence of deep soil compaction and quantity of yield reductions are not well known outside of the scientific community. Moreover, the economic costs are rarely, if ever, projected for large regions that endured wet harvest conditions. Therefore, in the...
following sections, we review the scientific literature on the persistence and quantity of yield reductions. Based on the literature and the regional context for North Dakota and Minnesota, we then calculate and project the economic costs that we expect for the 2020 and 2021 crops.

2 | THE LITERATURE—YIELD REDUCTIONS FROM DEEP WHEEL-TRAFFIC COMPACTION

We reviewed the scientific literature for significant wheel-traffic effects on corn and soybean yields due to deep soil compaction (Table 1). Most reports indicate that the largest reductions to crop yields (i.e., 9–55%; Table 1) occur in the first 2 yr following wheel-traffic compaction. Of the data we extracted from the literature, a median (i.e., 50th percentile) yield reduction of 21% can be expected across these first 2 yr. Keller, Sandin, Colobi, Horn, and Or (2019) noted that agricultural machinery has increased in size and loads (e.g., two to four times greater) in recent decades. Additionally, they presented data that soil compaction often extends three to four times deeper (e.g., 24–36 inches [60–80 cm]) under such loads, which are beyond the reach of typical tillage implements (e.g., chisel plows). However, when we removed the data prior to 1980, the median yield reduction was still 20%. DeJong-Hughes and Coulter (2011) provided a local example of yield reductions in western Minnesota following the wet harvest of 2009. In that study, seven farms that had adjacent areas with and without deep wheel-traffic compaction (as evident by deep ruts) showed a similar range and median (16–17%) yield reduction in corn and soybean (Table 1). These fields were chisel plowed to fill and smooth ruts before planting. The yield losses that occurred over the following 2 yr were due to deep soil compaction below the tilled depth.

Longer-term residual effects on crop yield reductions can and do occur but tend to be less than 5% and occur during inclement weather years. Interestingly, the yield reduction trends reported for corn and soybean appear to be very consistent for a large variety of other annual crops across the world (see reviews by Chamen, Moxey, Towers, Balana, & Hallett [2015] and Häkansson et al. [1987] ). Therefore, the information and economic analysis that we report here may be translatable to other crops and regions after updating the inputs with the appropriate land area, typical crop yields, and sell prices.

Deep soil compaction does cause yield reductions, but wheel traffic does not affect all fields or all portions within fields. For instance, Duttmann, Schwanebeck, Nolde, and Horn (2014) reported that up to 63% of corn silage fields were trafficked during one harvest. Kroulik, Kumhala, Hula, and Honzik (2009) also reported that 87–95% of field areas were trafficked at least once during an annual crop cycle. However, Duttmann et al. (2014) reported that only a portion of the harvest wheel traffic (i.e., 16–27%) caused tire-contact stresses high enough to induce substantial deep soil compaction. The proportion of trafficked areas that induces substantial compaction has increased over time and will likely continue to increase with the size of modern agricultural equipment (Keller et al., 2017; Keller et al., 2019). Unfortunately, there is no reporting system for producers to indicate the proportion of their harvested fields that they suspect deep wheel-traffic compaction was significant or at least noteworthy. Moreover, there is also no currently used technology or method for providing regional-scale land area estimates for soils that endured wheel-traffic-derived deep compaction. Although this information is lacking, we provide economic costs projections in the following section as graphs, where the projected costs are proportional to the fraction of land area with wheel-traffic compaction.

3 | ECONOMIC COSTS PROJECTIONS FOR THE 2020 AND 2021 CROPS

We projected state-level economic costs for the upcoming 2020 and 2021 corn and soybean crops in North Dakota and Minnesota. The projections were based on inputs of state-level data that are publicly available through the Farm Business Management Association’s FINPACK farm financial database (FINBIN, 2020) and the Iowa State University Farm Custom Rate Survey from 2017 through 2019. Using data from the scientific literature (Table 1), we assume the median of 21% crop yield reduction for the next 2 yr for land areas impacted by deep wheel-traffic compaction during the 2019 harvest. We also include estimates for the cost for a one-time leveling/smoothing (i.e., two passes of chisel plowing) of wheel-traffic ruts that were prevalent on these compacted areas in the fall of 2019.

Our projections only account for dollars lost from yield reductions and the expenses to level wheel-traffic ruts. The projections do not include economic costs due to externalities, such as soil erosion, flooding, nutrient losses, and so on.
### TABLE 1 Yield reductions reported in the scientific literature from one-time deep wheel-traffic compaction events

| Reference | Crop                  | Country          | Yield reductions | 1st year | 2nd year |
|-----------|-----------------------|------------------|------------------|----------|----------|
| Abu-Hamdeh (2003) | Corn                  | Jordan           |                  | 27%      | 14%      |
| Alblas, Wanink, van der Akker, and van der Werf (1994) | Corn silage         | Netherlands      |                  | 15%      | NA       |
| Botta, Tolon-Becerra, Lastra-Bravo, and Tourn (2010) | Soybean              | Argentina        |                  | 20%      | 15%      |
| De Jong-Hughes and Coulter (2011) | Corn                  | USA              |                  | 17%      | NA       |
| Gameda, Raghavan, McKyes, Watson, and Mehuys (1994) | Soybean              | USA              |                  | NA       | 16%      |
| Gultney, Krutz, Steinhardt, and Liljedahl (1982) | Corn                  | USA              |                  | 55%      | 25%      |
| Håkansson, Voorhees, and Riley (1988) | Corn                  | USA, Canada      |                  | 10%      |          |
| Nevens and Reheul (2003) | Corn silage          | Belgium          |                  | 13%      | NA       |
| Phillips and Kirkham (1962) | Corn                  | USA              |                  | 11%      | NA       |
| Phillips and Kirkham (1962) | Corn                  | USA              |                  | 22%      | NA       |
| Phillips and Kirkham (1962) | Corn                  | USA              |                  | 24%      | NA       |
| Phillips and Kirkham (1962) | Corn                  | USA              |                  | 36%      | NA       |
| Phillips and Kirkham (1962) | Corn                  | USA              |                  | 53%      | NA       |
| Raghavan, McKyes, Taylor, Richard, and Waterson (1979) | Corn                  | Canada           |                  | 50%      | NA       |
| Sidhu and Duiker (2006) | Corn                  | USA              |                  | 36%      | 7%       |
| Wolkowski and Lowery (2008) | Corn                  | USA              |                  | 28%      |          |
| Wolkowski and Lowery (2008) | Corn                  | USA              |                  | 14%      |          |
| Wolkowski and Lowery (2008) | Corn                  | USA              |                  | 42%      |          |
| Wolkowski and Lowery (2008) | Corn                  | USA              |                  | 9%       |          |

Summary

|                      | 1st year | 2nd year |
|----------------------|----------|----------|
| 25th percentile      | 15%      | 14%      |
| 50th percentile      | 25%      | 16%      |
| 75th percentile      | 40%      | 27%      |
| 25th percentile—combined years |          | 15%      |
| 50th percentile—combined years |          | 21%      |
| 75th percentile—combined years |          | 35%      |

*NA = not available since data was not collected and reported in the publication. *Mean yield reductions reported, but time since the deep wheel-traffic compaction event not reported. *Median yield reduction.

(Chamen et al., 2015) or other feedbacks, such as returns on agricultural research from commodity group funds. Therefore, the analysis presented here is a conservative estimate. We argue these to be the minimum economic costs due to deep wheel-traffic compaction during harvest activities.

Table 2 provides a detailed example of the inputs, calculation, and outputs of our projections. Figure 1 provides graphs of the economic costs as functions of grain sell prices and fraction of land area impacted by wheel-traffic compaction. The graphs cover a range of grain sell prices observed in the United States during the previous decade. The graphs also
TABLE 2  Calculation of economic costs for corn during 2020 and 2021 in North Dakota (ND) and Minnesota (MN) due to a one-time deep wheel-traffic compaction during the 2019 harvest. Accurate estimates of land area impacted by deep compaction currently do not exist. Therefore, the projection is for every 10% of planted area (i.e., 0.1 fraction of area; an arbitrary value) with a 21% yield reduction (see Table 1).

| Statement | Input/output | Units |
|-----------|--------------|-------|
| Mean 3-yr \(^{3}\) corn yield for ND | 147.1 | bu/ac |
| Mean 3-yr corn yield for MN | 187.0 | bu/ac |
| Mean 3-yr corn sell price for ND | $3.14 | USD/bu |
| Mean 3-yr corn sell price for MN | $3.43 | USD/bu |
| Wheel-traffic compaction on acres to be planted to corn | 10 | % |
| Mean 2-yr yield loss from wheel-traffic compaction | 21 | % |
| Number of tillage passes to level ruts | 2 | unitless |
| Cost per acre for tillage pass \(^{7}\) | $17.75 | USD |
| Anticipated area to be planted to corn in ND per year | 3,356,667 | acres |
| Anticipated area to be planted to corn in MN per year | 7,916,667 | acres |

Then,

2020 and 2021 economic cost for corn = 2(a + b) + c

where

\[ a = \text{ND yield losses yr}^{-1} = 147.1 \times 3.14 \times 0.10 \times 0.21 \times 3,356,667 \]

\[ b = \text{MN yield losses yr}^{-1} = 187.0 \times 3.43 \times 0.10 \times 0.21 \times 7,916,667 \]

\[ c = \text{ND and MN costs to level ruts} = 17.75 \times 2 \times 0.10 \times 1,000,000(3.357+7.917) \]

Total 2-yr cost for corn: $318.6 million USD

If,

Mean 3-yr soybean yield for ND | 35.6 | bu/ac |
Mean 3-yr soybean yield for MN | 47.9 | bu/ac |
Mean 3-yr soybean sell price for ND | $8.59 | USD/bu |
Mean 3-yr soybean sell price for MN | $8.81 | USD/bu |
Wheel-traffic compaction on acres to be planted to soybean | 10 | % |
Mean 2-yr yield loss from wheel-traffic compaction | 21 | % |
Number of tillage passes to level ruts | 2 | unitless |
Cost per acre for tillage pass | $17.75 | USD |
Anticipated area to be planted to soybean in ND per year | 6,533,333 | acres |
Anticipated area to be planted to soybean in MN per year | 7,600,000 | acres |

Then,

2020 and 2021 economic cost for soybean = 2(a + b) + c

where

\[ a = \text{ND yield losses yr}^{-1} = 35.6 \times 8.59 \times 0.10 \times 0.21 \times 6,533,333 \]

\[ b = \text{MN yield losses yr}^{-1} = 47.9 \times 8.81 \times 0.10 \times 0.21 \times 7,600,000 \]

\[ c = \text{ND and MN costs to level ruts} = 17.75 \times 2 \times 0.10 \times 1,000,000(6.533+7.600) \]

Total 2-yr cost for soybean: $269.0 million USD

Combined costs for corn and soybean: $587 million USD

\(^{3}\) Values from the Farm Business Management Association database (FINBIN) for North Dakota and Minnesota (FINBIN, 2020) using the Crop Enterprise Analysis for years 2017–2019. \(^{7}\) All 3-yr mean values are from 2017–2019 data. \(^{7}\) Iowa State University Farm Custom Rate Surveys from 2017 through 2019.

We project that North Dakota and Minnesota will have an economic cost of US$587 million for every 10% of the corn–soybean acres affected by deep wheel-traffic compaction during the 2019 harvest (i.e., yield loss and expense of leveling ruts). However, the actual fraction of total acres affected is unknown. It is important to note that these estimates are based on values from the FINPACK database (FINBIN, 2020). When state-level values from the USDA National Agricultural Statistics Service database were used in the projections, cover a range of land areas impacted by deep wheel-traffic compaction that are reasonably expected in producer’s fields (Duttmann et al., 2014).
FIGURE 1  Projections of economic costs for 2020 and 2021 due to deep wheel-traffic compaction during the 2019 harvest. Projections are a function of planted area affected by deep wheel-traffic compaction. Projections also assume a 21% yield reduction in areas affected by deep wheel-traffic compaction (see Table 1). Lines on a graph indicate differing grain sell prices. Grain prices near the 3-yr mean (i.e., 2017–2019) are in red text. The economic costs were estimated to be US$570 million for every 10% of acres affected. Therefore, these types of cost projections may have ∼3% sensitivity to the database used.

The actual total costs to North Dakota and Minnesota may range from US$0 to $1.76 billion if grain sell prices remain stationary through 2021 (Figure 1). This range in actual costs is based on land fractions (i.e., up to ∼30% of area) for individual fields as reported by Duttmann et al. (2014). These costs are expected to be the accumulation over both the upcoming 2020 and 2021 crops. The unknown, or movable, factor is a precise input for the fraction of land affected by wheel-traffic compaction. Compaction was clearly widespread throughout the region based on farmer and agricultural consultant’s anecdotes as well as an abundance of ruts in fields from combining and grain wagons. However, the input value is currently arbitrary due to the lack of precise data. Therefore, the graphs may be useful to scale the economic cost by land area as well as by any changes in grain sell prices. Another movable factor is the percentage yield loss due to deep wheel-traffic compaction. We reviewed and analyzed articles in the scientific literature that reported significant corn and soybean yield consequences following deep wheel-traffic compaction that tillage, used to fill and smooth ruts, did not alleviate. As noted above, these yield losses have a large range from 9 to 55%, with a 21% median. Although this median value is similar to our local example from DeJong-Hughes and Coulter (2011), there appears to be insufficient data in the literature to describe if these losses are functions of a location’s yield potential, crop genetics, root morphology, or other factors. Therefore, the 21% yield loss used here is also readily adjustable in our equation in Table 2. This value can be updated based on future research or on local examples for other regions.

Additional feedback consequences, other than environmental externalities, can also occur. For example, another economic cost results from fewer dollars going to research efforts through commodity boards. Agricultural research is well known to have a high return on investment, with estimates near 40:1 (Fuglie & Heisey, 2007). To estimate the costs on commodity-board research funds, we estimate that for every 10% of planted acres being affected by compaction, there is a $497 million cost from actual grain sells (i.e., total economic cost of $587 million minus the $90 million costs associated with leveling ruts; Table 2). If 0.5% of grain sells goes to check-off dollars for commodity groups (equal to $2.48 million), and 50% of those dollars go into funding research projects, then there is a cost of $1.24 million towards research. By assuming a 40:1 return on investment, we estimate that $49.7 million in economic gains will be forgone due to missed opportunities for agricultural research innovations.

4 CONCLUSIONS, FUTURE OUTLOOKS, AND NEEDS

Economic costs due to deep wheel-traffic compaction following a wet harvest, such as that in 2019 in the north-central and upper Midwest regions of the United States, may be substantial. However, the true cost is unknown and cannot be calculated precisely due to the lack of information on the fraction of land that is affected by deep compaction. The projections estimated here are for the upcoming 2020 and 2021 crops in North Dakota and Minnesota and premised on a “per 10% of land impacted” basis. However, wet conditions at harvest and other times of field operations reoccur in time. Therefore, similar costs will repeat in the future (Chamen et al., 2015). Climate projections predict an increase in the occurrence of wet field conditions during spring planting and late fall harvests (Morton, Hobbs, Arbuckle, & Loy, 2015; Swain & Hayhoe, 2015), which implies these costs will occur more frequently over time. To intensify agricultural crop production successfully and sustainably for the future, there needs to be purposeful efforts to minimize crop losses and minimize inputs. As
for solutions, the most effective way to decrease costs from deep wheel-traffic compaction is to reduce its occurrence rather than rely on remediation practices. Development and promotion of government policies that may help encourage producers to stay off wet, soft soils at high-risk periods for deep compaction are encouraged among the agricultural community. Such policies may include incentives for practices that reduce the occurrence of field traffic during the wet fall month. For example, a diversified crop rotation that expands beyond a two-phase, corn–soybean rotation to include shorter season crops would allow for one-third of acres to be harvested earlier during drier periods of the year, thereby reducing the potential economic costs of deep compaction by ~33%. Incentives for conservation practices that promote soil drying in late fall (e.g., interseeded cover crops) is also encouraged.

Currently, there is a need for precise large-scale reporting or sensing of deep wheel-traffic compaction in agricultural fields to assess adequately the actual magnitude of economic costs. Additionally, the persistence of yield reductions may likely extend farther out than just two years as heavier equipment means (a) deeper compaction and (b) less likelihood and effectiveness for mechanical and natural alleviation of soil compaction (Keller et al., 2017 and 2019). Additionally, these economic projections are valid even if a substantial number of compacted fields go into the preventative plant program for 2020. The yield reductions on those acres will be realized during the 2021 and 2022 crops.

The information and projections provided in this commentary are intended to help bring awareness to the scope of soil compaction on agricultural economics, so that industry can weigh options appropriately when faced with difficult decisions at harvest. This will also help producers, government agency personnel, industry, and researchers plan ahead for the next two years and for similar circumstances that will occur in the future.

CONFLICTS OF INTEREST
The authors claim no conflicts of interest.

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How to cite this article: Daigh ALM, DeJong-Hughes J, Acharya U. Projections of Yield Losses and Economic Costs Following Deep Wheel-traffic Compaction During the 2019 Harvest. *Agric Environ Lett*. 2020;5:e20013. https://doi.org/10.1002/ael2.20013