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The invisible subsoil compaction risk under no-till farming

Thomas Keller[a,b,1,2], Samuel Bickel[c,1], and Dani Or[d,e]

Affiliations are included on p. 6.

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No-till (NT) is a key component of conservation agriculture aiming at producing crops with minimal soil disturbance. This land management practice offers numerous economic and ecological advantages over conventional tillage as evidenced by its rapid expansion since the 1960s, now practiced on 15% of the global arable land. Nevertheless, various crops exhibit persistent yield losses even decades after transition to NT. Here, we demonstrate that the promise of beneficial and sustainable soil management may be undermined by a gradual and invisible threat of subsoil compaction. We report on a risk of subsoil compaction stemming from the episodic passage of heavy machinery (e.g., harvesters). The threat is of dynamic and asymmetric nature whenever compaction events occur more frequently than the natural rates of soil structure recovery, resulting in a gradual increase in soil degradation. Our analyses show that nearly 40% of global NT lands (0.8 million km^2) are under high subsoil compaction risk (primarily in heavily mechanized Canada, United States of America, and Brazil). Awareness and mitigation of subsoil compaction by scaling field operations to soil mechanical limits and adoption of smaller robotic vehicles will contribute to a sustainable and holistic conservation agriculture.

arable farming | subsoil compaction | conservation tillage | farm machinery

Significance

No-till (NT), a key component of conservation agriculture, is presently practiced over 15% of global arable land. NT offers economic and ecological advantages over conventional tillage; however, it may result in persistent yield losses for certain crops. Here, we highlight an invisible threat to sustainable soil management under NT due to subsoil compaction. We describe a subsoil compaction risk driven by compaction events due to heavy farm vehicles occurring at intervals shorter than soil structure recovery times. Our analyses show that nearly 40% of global NT lands face a high subsoil compaction risk. Mitigating this risk through scaling of farm machinery to soil mechanical limits is essential to sustaining and realizing the full ecological and agronomic benefits of conservation agriculture.

Crop production must meet the demands of rapidly growing human population, while balancing environmental impacts of modern agriculture (1, 2). Perceptible effects of climate change with frequent weather extremes are already challenging crop production and food security (3–5). Arable land management plays a pivotal role in addressing these challenges due to its direct effects on crop yields (6) and due to its potential to reduce the environmental footprint of arable farming (7) and its regulatory role in carbon sequestration for mitigating climate change impacts (8, 9).

While tillage has been practiced for millennia to create favorable conditions for uniform germination and subsequent crop growth, it requires considerable energy and may have detrimental environmental consequences ranging from soil erosion, loss of soil organic carbon to decline in soil biodiversity (10–13). Conservation agriculture manages crop production by maintaining permanent soil cover and diverse crop rotations while minimizing soil disturbances (14, 15). In the following, we focus on no-till (NT)—a key component of conservation agriculture—that has been adopted at increasing rates since the 1960s and is now practiced on approximately 15% of the global arable land (15). NT shortens the time required for crop establishment, reduces fuel consumption, and decreases labor per hectare (16) but may incur persistent yield penalties (6) and may require additional inputs [e.g., herbicides; (17)].

Globally, most of the NT areas are in North America, South America, and Australia (15, 18). These regions are characterized by big farm sizes (19) that require high-capacity agricultural machinery (e.g., combine harvesters with wide cutter boards and large grain tanks). The reliance on large and heavy farm vehicles that induce high mechanical soil stresses (Fig. 1*A*) is likely to result in soil compaction in the crop root zone (20, 21). Hence, while NT practices confer numerous agroecological and economic benefits, even the occasional use of large and heavy machinery [e.g., laden combine harvesters with wheel loads now exceeding 10,000 kg; (21)] remains a major concern. Moreover, the absence of mechanical loosening (i.e., tillage) in NT systems implies reliance on natural mechanisms for soil loosening, and consequently, NT soils are typically more compact than tilled soils (Fig. 1*B*).

While direct measurements of the extent of the compaction problem and its legacy are limited at present, theoretical and anecdotal evidence suggests that part of the persistent yield losses associated with NT (6, 26) may result from chronic subsoil compaction. There are growing concerns of persistent soil compaction in NT fields in Brazil (27–30)—the second largest NT country in the world accounting for nearly 20% of the global NT area (15). We note that soil compaction problems in Brazil may be aggravated by the nature of tropical soils

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[1]T.K. and S.B. contributed equally to this work.

[2]To whom correspondence may be addressed. Email: thomas.keller@slu.se.

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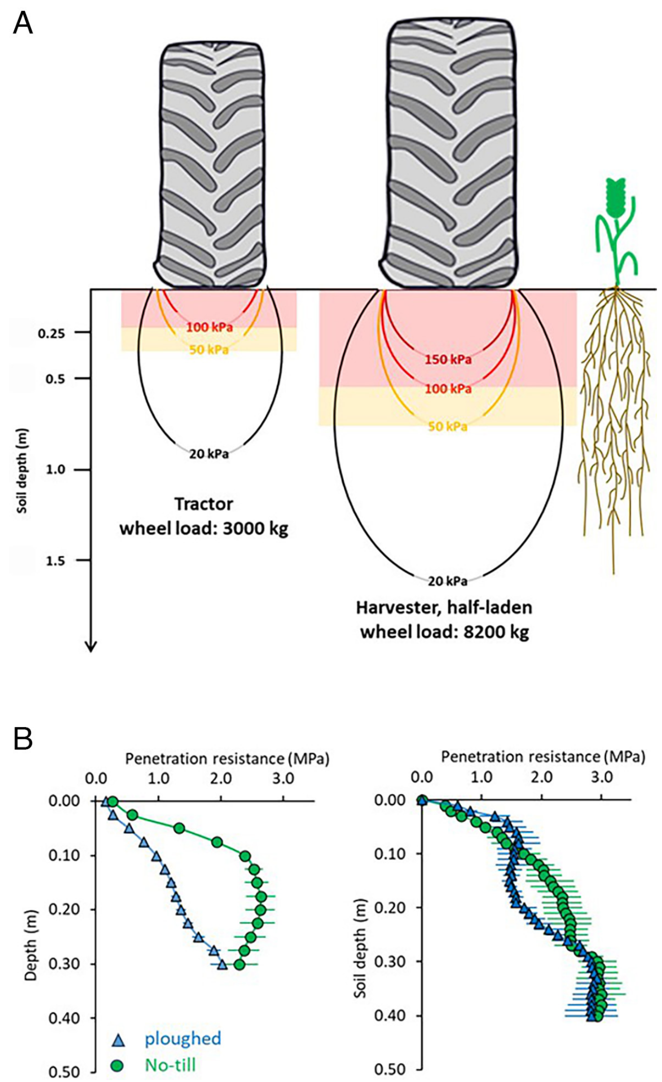

Fig. 1. Loads of modern farm machinery induce high stress levels into deep soil layers with associated enhanced risks of soil compaction in the root zone. (*A*) Simulated vertical stress under the tire of a large tractor (*Left*) and a modern combine harvester (*Right*). The 50 kPa isobar indicates a critical stress level to prevent soil deformation under moist conditions (22). Root system of winter wheat (*Triticum* L.) at harvest is shown for comparison (redrawn from ref. 23). (*B*) Illustrative examples of measured depth profiles of cone penetration resistance, indicative for root elongation rates (24), in NT and plowed soils from field experiments in the United States of America [*Left*; (25)] and from farmers' fields in Sweden (*Right*; see *Materials and Methods*). Symbols show means per depth and horizontal bars are SE.

that often contain nonswelling clay minerals (31, 32) with limited potential for intrinsic soil structure regeneration (33, 34). The largest NT areas in temperate regions of the United States of America and Canada [together accounting for one third of global NT area; (15)] are associated with wet subsoils (35) and limited harvest windows (36, 37) that jointly result in conditions susceptible to soil compaction. Hence, a major part of global NT area is characterized by factors enhancing soil compaction risks and persistence: heavy machinery, moist soil conditions under critical field operations, and/or limited potential of natural recovery following compaction.

The aim of this study is to identify and highlight the unseen risk of subsoil compaction under NT farming considering persistent trends in farm mechanization. Specifically, we argue that the common perception of optimal land management by virtue of NT alone may be misleading if peak loads—even a single passage of a combine harvester per year—are not properly managed. We delineate the global arable lands at risk, discuss the problem of gradual increase in subsoil compaction levels by considering realistic values for compaction frequency and soil structure recovery times, and outline solutions toward sustainable NT farm vehicle design and use. The primary message is that prevention of subsoil compaction must become a central component of conservation agriculture for sustainable soil management.

Global Patterns of Subsoil Compaction Risk Under NT Farming

Irrespective of soil management specifics, the global patterns of crop yield losses due to soil compaction (38) and global distribution of subsoil compaction susceptibility (21) reveal a similar picture of enhanced risks of subsoil compaction in regions with intensive mechanization (i.e., large farms with heavy tractors and harvesters) combined with moist subsoil conditions. In Fig. 2, we combine a global map of subsoil compaction susceptibility index (SCSI) developed by Keller and Or (21) with a global gridded tillage dataset of Porwollik et al. (39) to test whether regions with extensive NT management harbor higher risk of subsoil compaction. The global extent of NT is approximately 15% of total arable land (15, 40) amounting to approximately 2 million km^2 of land. The top five counties with the largest tracts of land under NT account for >80% of the total global NT area and are United States of America (430,000 km^2), Brazil (320,000 km^2), Argentina (310,000 km^2), Australia (220,000 km^2), and Canada (200,000 km^2). Except for Australia and parts of Argentina, NT lands are largely under high risk of subsoil compaction (as indicated by SCSI > 1.0; Fig. 2). The exceptions are attributed to moderate country-averaged mechanization levels in Argentina (41) and relatively dry conditions [i.e., low climatic soil water contents; (31)] in Western Australia. A high subsoil compaction risk is also predicted for parts of Europe but arable land under NT there is less than 5% (15). Based on our analyses, we estimate that about 40% of all NT land (0.8 million km^2; Fig. 2*C*) is under high subsoil compaction risk (primarily in Canada, United States of America, and Brazil).

To gain additional insights on potential impacts of soil tillage on crop yields in rainfed agriculture across various conditions, we present in Fig. 3 a summary of the combined meta-analyses of Pittelkow et al. (6, 26) and Su et al. (42) for various crops. We focus here on maize and wheat—two major global crops (43)—and consider the elapsed time since conversion to NT (Fig. 3*A*) and response under different climatic regimes (Fig. 3*B*). The results show that wheat is a more robust crop than maize to NT transition, exhibiting only minor yield losses. In contrast, maize yields are persistently lower under NT [relative to conventional tillage (CT)] across time since transition and for humid climatic conditions (Fig. 3). We note that maize is more sensitive to soil compaction than wheat: a global meta-analysis by Obour and Ugate (44) revealed that on medium-textured soils [such as loam, the most dominant texture class globally; (45)], grain yields are decreased due to soil compaction by 34% in maize but only by 6% in wheat. This is consistent with a stronger reduction (compared with CT) in root biomass in maize than in wheat in compact soil layers under NT reported by Fiorini et al. (46). We hypothesize that the persistent trend toward lower yields with time since NT conversion for maize (Fig. 3*A*) can be attributed to accumulative compaction effects over time. Yield penalties under NT tend to increase in wet climate in both wheat and maize (Fig. 3*B*), which might be associated with higher compaction risks in moist soils. These hypotheses remain to be tested in future research.

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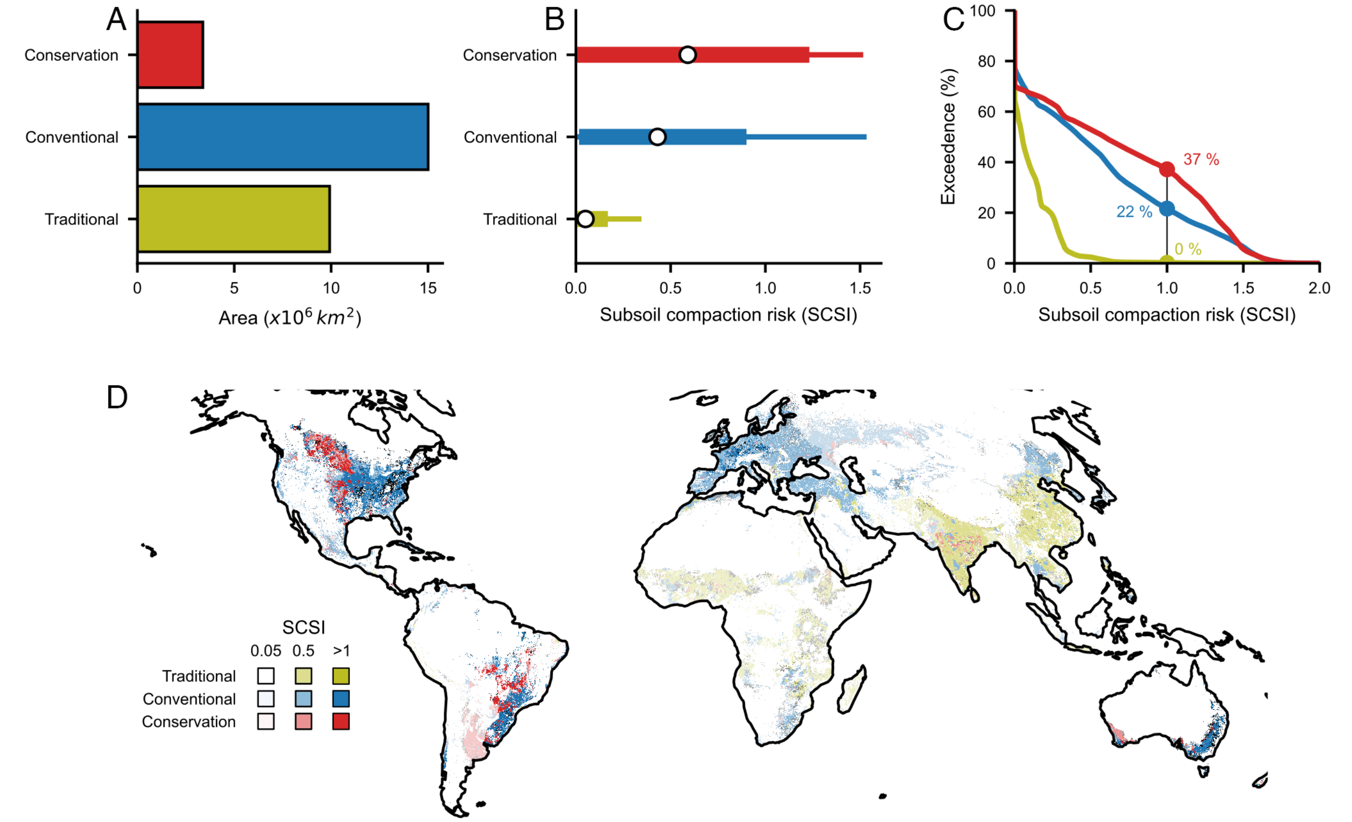

Fig. 2. Analyses of global subsoil compaction susceptibility for different soil tillage systems. (*A*) Total area under three primary soil tillage systems. (*B*) SCSI values for different tillage systems, with SCSI > 1 indicating high compaction risk. (*C*) Global SCSI exceedance probability for different tillage systems. (*D*) Global geographical distribution of SCSI for different tillage systems with dark colors indicating high compaction risk (SCSI > 1) and light colors low risk (SCSI < 1).

The combined analyses as shown in Figs. 2 and 3 lend support to the hypothesis that yield losses in NT farming can be attributed in part to subsoil compaction. Further support to this hypothesis stems from documented higher soil bulk density and enhanced mechanical resistance to root growth in NT soils (Fig. 1*B*), reports of compaction problems in long-term NT fields (27–29), and crop yield benefits of occasional subsoiling in NT systems (47, 48). The increased vulnerability to subsoil compaction under high mechanization levels even in NT farming are linked with high loads applied to soils (e.g., for annual harvest) causing the propagation of soil mechanical stresses into deep soil layers (21). Additionally, we need to consider that NT is practiced in some of the most productive areas (49) receiving sufficient precipitation relative to potential evapotranspiration (50), resulting in moist soil conditions, low soil mechanical strength and enhanced compaction risks (21). Even though crops in areas of high mechanization levels may receive sufficient amounts of nutrients via fertilization, restricted access of crop roots to subsoil resources (nutrients, water) decreases crop yields in rainfed agriculture, especially in dry years (51–53).

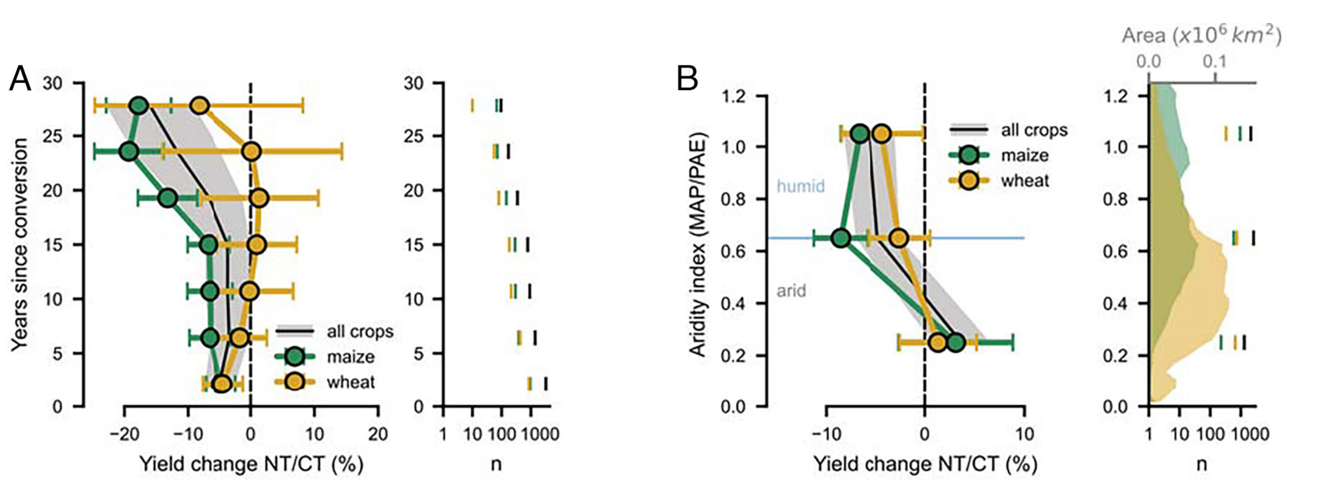

Fig. 3. Meta-analyses of yields for maize and wheat under NT and CT. (*A*) Comparing rainfed maize and wheat yields as a function of time since transition to NT management relative to CT; note the number of paired samples (n) for each time are listed on the right. (*B*) Maize and wheat crop yield changes in different climatic zones expressed as Aridity index as mean annual precipitation (MAP) divided by potential annual evaporation (PAE); note the area under each climate and number of paired samples on the right.

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Gradual Subsoil Compaction: When Intervals between Compaction Events Are Shorter than Soil Structure Recovery Times

Gradual subsoil compaction results from two opposing processes characterized by disparate time scales: instantaneous soil deformation induced by field traffic (i.e., heavy farm machinery) and a much slower natural soil recovery following compaction (54). Hence, while soil degradation can be caused within seconds (55, 56), detrimental effects on soil functions caused by compaction [i.e., crop yield loss, reduced water infiltration capacity, poor soil aeration; (57)] persist for years, decades, or even centuries (58–61). The decline in soil functions accumulated over time from the compaction event until full recovery constitutes the ecological and economic costs of soil compaction (54).

Acknowledging that a certain degree of soil compaction is unavoidable due to the necessity of field traffic for establishing and harvesting crops, it follows that soil can only be in dynamic equilibrium if recovery times are significant and shorter than the extent and duration between compaction events (Fig. 4*A*). However, if the period between compaction events falls below intrinsic soil structure recovery time, soil gradually degrades with time (Fig. 4*A*). To illustrate the likelihood of gradual soil degradation under realistic assumptions, we simulated the evolution of changes in soil void ratio for randomly assigned duration between compaction events [e.g., caused during harvest with a modern combine harvester that can have a mass of 40,000 kg when laden; (20)] of 1 to 5 y [i.e., heavy loads resulting in high soil stress and/or moist subsoil with associated low soil strength resulting in compaction risk every 1 to 5 y; (62)] and two recovery time scenarios [5- and 20-y recovery time, corresponding to typical natural recovery times in topsoil and subsoil, respectively; (54)] (Fig. 4*B*).

In the absence of mechanical subsoil loosening (i.e., tillage) in NT farming, the prospects of soil structure recovery following compaction rely entirely on natural soil structure recovery processes. These include abiotic processes (soil drying and wetting,

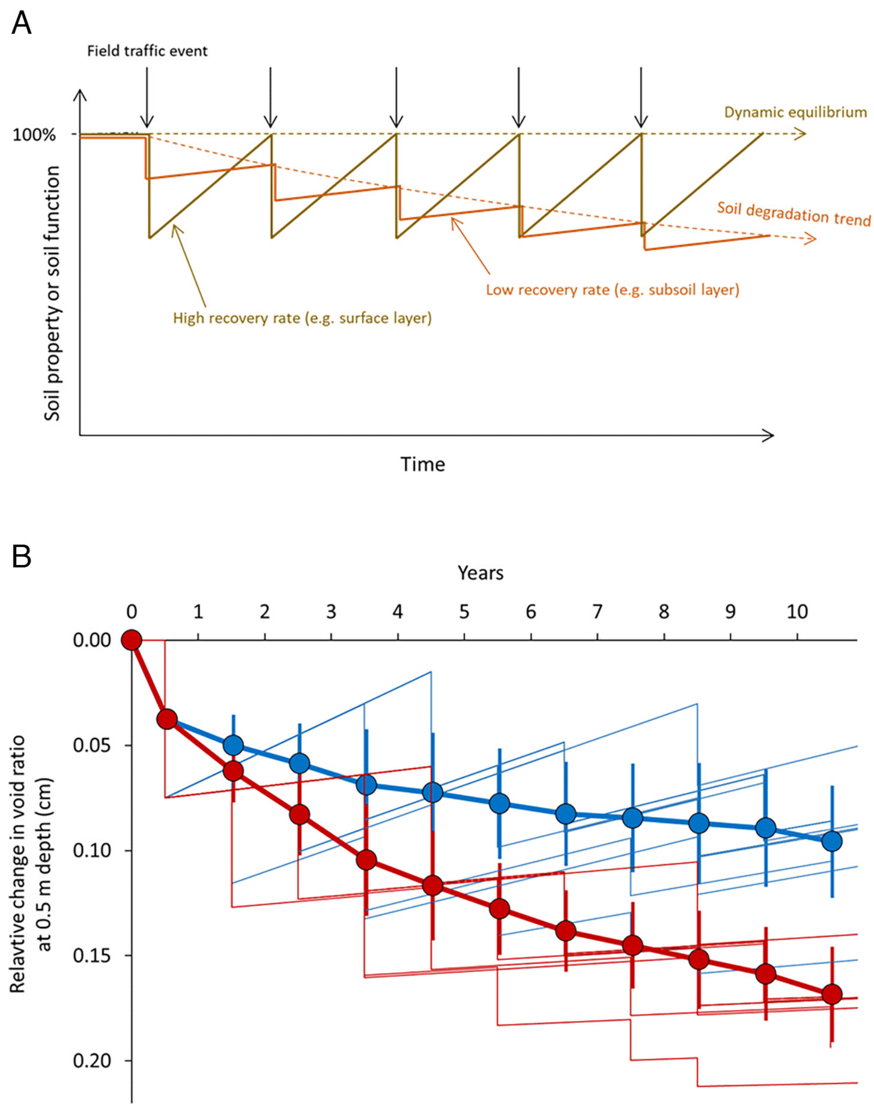

Fig. 4. Schematic illustration of the soil compaction problem resulting in gradual soil degradation. (*A*) Soil degradation due to field traffic and recovery following compaction events for a case where the frequency of perturbations (traffic events) and recovery time are in balance (brown lines) resulting in a dynamic equilibrium and for a case where time between perturbations is shorter than recovery time (red lines) resulting in accumulating degradation over time. (*B*) Simulated changes in void ratio over time for compaction events that randomly occur at time intervals of 1 to 5 y and for two different recovery times (blue: 5 y; red: 20 y). Thin lines show different realizations (interval between each compaction event is random between 1 and 5 y; 10 simulations per recovery time scenario) and symbols and bold lines show the mean of the 10 simulations. Recovery paths in (*A*) and (*B*) are drawn with constant recovery rates (lines) for simplicity—in reality, recovery is likely nonlinear and differs between soil properties. Note that subsequent deformation, illustrated by a decrease in soil property or function in (*A*) and a decrease in void ratio in (*B*), decreases with the number of loading cycles (*SI Appendix*, Fig. S1), and hence, soil degradation trends approach a horizontal asymptote.

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and freeze–thaw cycles), and biotic processes related to biological activity of soil fauna (e.g., biopore formation, translocation of soil particles), soil microorganisms (e.g., binding of soil particles), and plant roots (e.g., biopore formation, enmeshing of soil particles). While a quantitative analysis of compaction recovery rates for different soils and climates is currently not possible due to lack of data and suitable mechanistic models (see, e.g., ref. 54), a qualitative discussion of differences in soil structure recovery potential between major global NT regions is possible.

Soil shrinkage and swelling, which result in particle rearrangement and formation of new pore spaces, require expansive clay minerals in a soil. However, several major global NT areas—including Brazil, western Australia, and North America—are dominated by nonexpanding clay minerals (such as kaolinite and illite) in top- and/or subsoils (31, 32) reflecting low soil structure recovery potential. Freezing, particularly in the subsoil, is absent in important NT areas except Northern America (63) and can therefore not support soil structure recovery in most major NT areas of the world. Soil biological activity including root growth and faunal activity in cold (such as North America) and dry climate (such as western Australia) is restricted to periods of adequate temperature and sufficient soil moisture (64–67), while conditions in South America allow enhanced soil biological activity. However, the possibility of growing two crops within a year in parts of South America (68) decreases the time between potentially harmful compaction events thereby increasing the likelihood of attaining a soil degradation trajectory (Fig. 4). In summary, the potential of soil structure recovery following compaction is limited in most major global NT areas, either due to limited soil shrink-swell capacity (Brazil) or due to cold (North America) or dry climate (western Australia) that reduce the windows of biological activity.

Reducing Subsoil Compaction Under NT Farming

While avoidance of soil compaction is simple in principle, namely by selecting machinery that exert soil stresses below soil strength during agronomic operations (69), this may not be feasible in practice. Food production under economically viable conditions requires machinery, while favorable soil conditions (i.e., sufficiently dry to support vehicle loads) may not coincide with optimal timing for field operations in relation to crop cycles such as sowing or harvesting. Vehicle-induced soil stresses can be partially reduced by technical solutions (e.g., wider tires, rubber tracks); however, these pertain to soil surface with limited effect on the subsoil (70) that is particularly vulnerable because of the decade-long compaction-recovery times (71). Postcompaction soil recovery rates can be enhanced by promoting biological activity [e.g., by use of "bio-tillage" crops; (72, 73)], however, these are unlikely to overcome the compaction problem simply because soil structure recovery times are much longer than intervals between field operations (Fig. 4). Controlled traffic-farming restricts all field traffic to designed permanent tramlines and is a system to manage soil compaction suitable to many major NT areas (74), which has shown to increase crop yields and reduce surface water run-off and greenhouse gas emissions (74, 75). However, the system creates permanent, heavily compacted tracks, which may strongly hinder soil biological activity or could limit water infiltration and change flow paths with potential consequences for water recharge and which could make future changes in soil management and land use problematic. Autonomous vehicles and fleets of robots seem to offer new possibilities to break the reliance on heavy machinery for efficient farming. Some autonomous low-weight vehicles offer a way forward, although challenges, e.g., related to harvesting operations, remain (20). The use of autonomous electric light machinery may already now be beneficial if ecological costs of soil compaction and climate impact were accounted for (76). Although challenges remain, recent studies have shown the potential of autonomous machinery in arable cropping systems, with positive impacts on farmers' incomes under certain conditions (77, 78).

NT farming and conservation agriculture must reflect a commitment to not only minimize soil disturbance by avoidance of tillage but also to minimize soil deformation by avoiding peak loads that exceed soil strength, particularly in the invisible subsoil with low compaction-recovery potential, to truly fulfill the claim of soil conservation. Timely adoption of strategies for mitigating subsoil compaction risk is particularly important for regions with currently low but rapidly increasing mechanization level (e.g., China). Drivers of soil compaction are rooted in the need for the capacity of agricultural field operations to comply with constraints set by complex interactions involving farm economy, intermediate trade, machine manufacturers, national economic systems, and world economy (e.g., commodity market). A systemic change toward sustainable soil management based on light machinery therefore needs to involve the complete agricultural value chain.

Conclusion

We highlight the potential of an invisible threat to the sustainability of NT due to persistent subsoil compaction risk stemming from reliance on efficient, high-capacity farm machinery, even when soil is not disturbed (i.e., not tilled). We show that NT farming is concentrated in regions with large field and farm sizes, which require large and heavy machinery that induce high stress levels. Major NT areas are in temperate climate with occasionally moist subsoil that is prone to compaction, resulting in a situation where vehicle-induced soil stresses frequently exceed soil strength. We estimate that almost 40% of the global NT area is at high subsoil compaction risk. The fact that soil structure recovery times are typically much longer than intervals between compaction events implies a risk of a gradual increase in soil degradation. Data suggest that yield losses of certain crops (e.g., maize) under NT may be attributed to subsoil compaction. Advances in autonomous light-weight vehicles offer a potential to disentangle the link between heavy machinery with associated high subsoil compaction risks and competitive and economical food production. We conclude that avoidance of subsoil compaction by minimizing peak loads (e.g., during harvest) must become a central component of NT farming and conservation agriculture for sustainable soil management.

Materials and Methods

Soil Stress Simulations. Stress propagation in soil below agricultural tires (Fig. 1*A*) was modeled using the classical Boussinesq (79) solution in relation to the problem of the normal loading of the surface of a homogeneous isotropic elastic halfspace. For simplicity, we assumed a circular shape for the contact area (i.e., tire-soil area) and a uniform contact stress distribution across the contact area. Vertical normal stress, σ_{zz}, at depth z under the centerline of the contact area with radius a is then calculated as (79)

$$\sigma_{zz} = p_0\left(1 - \frac{z^3}{\left(a^2 + z^2\right)^{3/2}}\right), \quad [1]$$

where p_0 is the surface stress.

Soil Mechanical Resistance as a Function of Depth. Soil mechanical resistance in Swedish farmers' fields shown in Fig. 1*B* was measured in October 2024 using a hand-held Eijkelkamp penetrologger (cone base area 1 cm^2, cone apex angle 60°)

to a depth of 0.45 m. Two fields were selected: one field on a NT farm that has not been plowed since 1997 and has been under strict NT since 2008 (i.e., 16 y at the time of measurements) and one field on a farm that is conventionally tilled (i.e., regular moldboard plowing to approximately 0.2 m depth). The two fields are within 6 km from each other (central coordinates: 59.37 °N, 17.59 °E). In each field, five locations were selected, and at each location, ten insertions were made.

Changes in Void Ratio for Repeated Loading Events. Changes in void ratio due to loading shown in Fig. 4*B* were simulated for the 0.5 m soil depth (i.e., subsoil) under a wheel load of 8,000 kg (an average load for the front wheels of a modern combine harvester with half-full grain tank; 22, 23, 71) and a 900/60R32 tire with a load-adjusted tire inflation pressure of 150 kPa (https://terranimo.world) using the SoilFlex model (80). Soil stress–strain behavior was characterized by the O'Sullivan and Robertson (81) model, and the soil mechanical properties were calibrated based on measured data from repeated loading tests obtained from the literature including both laboratory studies (81, 82) and field studies (83, 84). These studies used soils with textures ranging from sand to clay (clay contents between 2 and 45%). Simulated relative changes in void ratio are compared with measured relative changes in void ratio in *SI Appendix,* Fig. S1. Hereby simulated stress levels were adjusted to applied stress levels of the respective studies.

To simulate changes in void ratio due to loading (i.e., decrease in void ratio) and recovery (i.e., increase in void ratio), loading events were simulated to randomly occur at time intervals of 1 to 5 y, with linear increase in void ratio between loading events (thin lines in Fig. 4*B*). Data about temporal dynamics of compaction risks are scarce. One exception is the study by Kuhwald et al. (62) who showed that in their study area, situations where soil stress is twice as high as soil strength [corresponding to their soil compaction index >0.3 and representing "very high" to "extremely high" compaction risk; (85)] occurred at least once within 5 y on 60% of the arable land in their study region (total study area in Lower Saxony, Germany: 2,000 km^2; MAP 649 mm, mean annual temperature: 10 °C). Soil compaction is induced when soil stress > soil strength (56) or even at lower ratios of stress to strength (81, 86, 87). This, in combination with the rather dry conditions (i.e., low MAP) in the study region considered by Kuhwald et al. (62), indicates that one compaction event every 1 to 5 y, as assumed here, is realistic and rather conservative. Two scenarios with recovery times of 5 and 20 y, respectively, were simulated (blue and red, respectively, in Fig. 4*B*). For simplicity, recovery was assumed to be linear. The chosen recovery times represent fast (5 y) and average (20 y) recovery in subsoil [see Keller et al. (54) and references therein]. For each scenario, 10 realizations, i.e., 10 sequences of random time intervals between loading events, were made (thin lines in Fig. 4*B*), and the mean across the ten realizations is indicated by filled circles with corresponding SD in Fig. 4*B*.

Global Subsoil Compaction Risk for Different Tillage Systems. Keller and Or (21) provide a detailed description of the SCSI calculations. In short, estimates of soil stress were based on average tractor size at the country level, which was calculated using i) global tractor density data, ii) a mechanization-level index, and iii) tractor power as a function of farm size. The approach results in representative estimates of subsoil stresses, comparable to those caused by contemporary combine harvesters. Based on soil texture and climate-averaged water content, the SCSI was determined by dividing the representative soil strength with the typical machinery-induced soil stress for a depth of 0.5 m (88). Applying higher stress than the soil's strength results in soil deformation and compaction (69, 89, 90). Locations with SCSI > 1.0 were therefore identified as regions that are susceptible to subsoil compaction. We note that deformation likely occurs at applied stresses smaller than the precompression stress (22, 81, 86), and hence irreversible soil deformation may already occur at SCSI < 1.0.

For calculating zonal statistics of tillage and NT regions, we aggregated a global gridded dataset classifying six different tillage systems (18, 39). We simplified the classification by combining the classes relating to conservation ("Reduced," "Conservation Agriculture"), conventional ("Conventional annual," "Rotational"), and traditional ("Traditional annual," "Traditional rotational") tillage systems. This grouping aligned well with the estimated mechanization-level used for calculating the SCSI (i.e., regions of low mechanization corresponded to regions with predominantly traditional tillage). Conservation agriculture emphasizes three main principles: minimum soil disturbance, crop rotation, and maintaining soil cover through crop residues (6). Although NT practices are not strictly required for conservation agriculture, they are considered a cornerstone of its implementation. Hence, for identifying the global regions at risk for subsoil compaction, we masked global SCSI values (21) at a resolution of 0.1 degrees (nearest neighbor interpolated) and calculated the areas and proportions of arable land at risk to subsoil compaction for the three different tillage systems.

Meta-Analysis of Yield Under NT with CT. We combined two global datasets (6, 42) on crop yields under NT and CT. After merging the data from Pittelkow et al. (n = 4,033) and Su et al. (n = 3,579), duplicate observations were removed based on the provided metadata [using columns "Author," "Year," "Journal," "Latitude," "Longitude," "Crop," "Study Duration"/"Years since NT started (yrs)"] retaining 7,052 observations in trials without irrigation. The joined data were further filtered to include only rainfed maize and wheat retaining 4,090 values of yield for CT and NT. The effect of tillage system was then analyzed with respect to i) the years since conversion from CT to NT, and ii) the soil water balance estimated by the Aridity index defined as the ratio of MAP to PAE (91). The PAE was calculated using solar radiation and temperature obtained from WorldClim 2 (92). To analyze trends, we binned both variables and calculated the effect size using the log response ratio of the average yield under NT and under CT, $L_{RR} = \ln\left(\overline{NT}/\overline{CT}\right)$, as well as the corresponding SE (93, 94). Binning was performed with even widths, and the number of samples per bin was reported. The effect size was indicated as percentage of yield change relative to CT, i.e., using $\left(e^{L_{RR}} - 1\right) \times 100\%$.

Data, Materials, and Software Availability. The dataset underlying the global map of subsoil compaction risk for different tillage systems has been deposited in Zenodo (https://doi.org/10.5281/zenodo.17144310). Data underlying the meta-analysis are available from previously published sources (6, 35, 42).

Author affiliations: [a]Department of Soil and Environment, Swedish University of Agricultural Sciences, 75007 Uppsala, Sweden; [b]Department of Agroecology and Environment, Agroscope, 8046 Zürich, Switzerland; [c]Institute of Environmental Biotechnology, Graz University of Technology, 8010 Graz, Austria; [d]Department of Environmental Systems Science, Swiss Federal Institute of Technology, 8092 Zürich, Switzerland; and [e]Department of Civil and Environmental Engineering, University of Nevada, Reno, NV 89557

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