

Soil Compaction During the Construction Process of a Vertical Agrivoltaic System

Analysing Vehicle Traffic and Modelling Its Impact on Wheat Yield

Jana Kalmbach¹ , Sebastian Gayler² , and Rhea Pöter^{1,*} 

¹Fraunhofer Institute for Solar Energy Systems ISE, Germany

²Department of Biogeophysics, University of Hohenheim, Germany

*Correspondence: Rhea Pöter, rhea.anna.poeter@ise.fraunhofer.de

Abstract. The construction process of agrivoltaic systems requires intense vehicle traffic and can pose the soil at risk of compaction. Vehicle traffic can reduce soil porosity and negatively impact water infiltration, root penetration, nutrient availability and overall crop productivity [1]. Despite mitigation through tillage and natural processes, compaction can be persistent, particularly below the tillage depth, and result in long-term agricultural challenges [2]. To assess the risk of soil compaction, this study analyzed vehicle traffic during the installation of a 2.4 MW_p vertical agrivoltaic system in the Black Forest region, Germany. Upon completion, soil conditions were assessed in areas exposed to varying traffic intensities. Based on the soil data, wheat growth was simulated from 2016 to 2020 with the simulation framework Expert-N. The areas adjacent to the agrivoltaic system on the shortest way to the storage area were exposed to most vehicle traffic, leading to visible turf damage, increased penetration resistance and a reduction in plant-available water capacity. In comparison to the less trafficked areas, simulated wheat yield was reduced by about 20%. The land loss for the studied vertical system is about 5.8%. Additionally, the total yield was estimated to be reduced by 4.9 to 6.4% due to compaction effects, depending on the reference scenario. While further evaluation with real crop data and long-term assessments are needed, this study provides initial insights into vehicle traffic during the installation of vertical agrivoltaics and its potential impact on soil and crop yield.

Keywords: Agrivoltaics, Soil Compaction, Vehicle Traffic

1. Introduction

Agrivoltaics is emerging as a promising solution to the dual challenge of meeting the growing global demands for food and renewable energy. By integrating photovoltaic (PV) systems into agricultural production, land use can be optimized while offering potential synergies between crops and PV panels. However, the construction process of agrivoltaic systems and the adapted agricultural management can pose soil locally at risk of compaction [3]. Soil compaction caused by agricultural machinery is a well-documented issue, with the risk of soil deformation increasing at higher soil moistures [1]. On the vehicle side, compaction is influenced by axle load, tire type, inflation pressure, contact area, operation time, number and frequency of passes, and velocity [4], [5]. While the effect of wheel loads and the number of passes is extensively researched, most studies focus on agricultural machinery, with typically higher wheel

loads than construction vehicles, but only few subsequent passes. Limited studies investigating multiple passes indicate that the effects of compaction may lessen with each subsequent pass; however, some research presents conflicting findings [6], [7], [8].

In the agrivoltaics sector, construction companies tend to originate from ground mounted PV or barn industries and may lack the awareness or expertise required to operate on agricultural soils [3]. Additionally, companies are often constrained by rigid and short project timelines, exacerbated by environmental protection measures for instance during bird breeding seasons, limiting their ability to adjust construction schedules to rainfall events and unfavorable soil moisture conditions [9]. Within the field of agrivoltaic research, studies focusing on soil compaction remain scarce, even though long-term land productivity is a major barrier to agrivoltaics for farmers [10]. Despite mandatory protective measures, local soil damage might occur, which can negatively impact crop yields and can have financial consequences. For instance in Germany, critical thresholds for soil damage are defined and construction companies can be demanded for recultivation measures and intercropping strategies [11]. However, subsoil compaction can be difficult to detect and crop productivity might decline even before reaching critical thresholds. Yield reductions have financial implications for farmers and in some countries, including Germany, yield requirements need to be fulfilled for agrivoltaics to qualify for financial benefits [12].

This research examined vehicle traffic during the installation of a vertical agrivoltaic system, and its effect on soil and yield. The system featured three PV panels sequentially stacked and mounted perpendicular to the ground in an east-west orientation. Compared to overhead systems, vertical systems require less work at greater heights, but the top PV row nevertheless reached 3 m height. After system installation, soil exposed to varying vehicle traffic intensities was assessed, and wheat yields were simulated over a five-year period based on this assessment. The objective was to gain a more comprehensive understanding of the effects of agrivoltaics on agricultural productivity by making an initial attempt to quantify the influence of compaction on yield.

2. Methodology

At the case study site, a 2.4 MW_p vertical agrivoltaic system and two small overhead systems were installed from July until end of November 2024 in the Southern Black Forest region, Germany. The site is predominantly characterized by Mollic Leptosol [13], except for a diagonally oriented central trough where soil has accumulated over time, forming colluvial deposits over Luvisol [14]. Soil assessments were conducted in the latter, because measurements were not possible in the Leptosol due to its high share of stones and low thickness. From July 29 to November 28, 2024, construction vehicles were tracked with two GPS sensors [15], magnetically attached to the construction vehicles' roofs and measuring position data in one second intervals. Tracked vehicles included a wheel and a telescopic loader, with the latter being replaced by a delta loader on October 15. The delta loader could only be tracked for a week. The overhead systems were not assessed because of insufficient soil depth and tracking inaccuracy within the system.

Further pathways, also for other vehicles, were estimated based on detailed information provided by the construction companies and manually drawn in QGIS [16]. Tracking data was processed by removing error locations and connecting data points to vehicle pathways, except if consecutive points exceeded a distance greater than 50 m after sensors exit sleeping mode. To analyse the vehicle traffic per PV interspace, the site was segmented into grid parcels with the width of the interspaces (typically 13.5 m) and a height of 13.5 m. In the perimeters of the PV system, the height or width was adapted to better fit the space between the nearest PV row and the fence. The number of passes per vehicle per grid cell were counted to determine the vehicle traffic intensities.

The traffic assessment covers the installation of the substation and grid connection, assembly of the substructure, PV modules, string cables, sub-surface cabling, and the solar fence (which also functions as vertical PV). Site preparation and the final removal of residual materials or construction equipment are excluded. As part of the soil protection concept, an access track was temporarily covered with protection mats for substation delivery in July, which required heavy vehicles. Additionally, the storage area was covered with metal protection mats throughout the installation and wood chips were available to be added on areas with turf damages. *Table 1* summarizes the vehicles used for PV assembly, their weight, estimated maximum additional load, and construction step.

Table 1. Vehicle weight, maximum additional load (excluding driver), and construction steps.

Vehicle	Weight (kg)	max. add. load (kg)	Step
Ramming vehicle	3,700	0	Ramming of foundation posts
Wheel loader	5,980	1,500	Delivery of substructure components, PV modules, inverter cables, and other electric components
Telescopic loader	9,470	0	Installation of PV modules
Scissor platform	8,260	500	Module assembly, string cabling
Excavator	6,411	0	Excavation and closing of cable trenches
Delta loader	4,076	700	Placement of inverter cables, delivery of sand for cable trenches, closing and leveling of cable trenches

After system installation and prior to any soil management, penetration resistance (PR), bulk density (BD), water retention and hydraulic conductivity curves were measured in November 2024. Measurements were conducted in four areas, representing 1) the main access track from the storage area to the northern PV rows, 2) an area with medium to high traffic intensity, temporarily covered with soil protection mats during the installation of the substation and grid connection, 3) an area with medium traffic intensity, and 4) an area with the lowest traffic intensity at the site (*Figure 1*). Within each category, measurements were taken at three locations with vehicle passes close to the respective mean number of passes. At each sample location, ten penetrations were conducted perpendicular to the PV rows (120 in total, 30 per category) with an Eijkelkamp penetrometer [17]. Soil cores were taken at 10 and 50 cm depth (only 2 soil core sample locations for category 2 and 3) and the hydraulic parameters [18] were estimated with Hyprop devices in the laboratory [19].

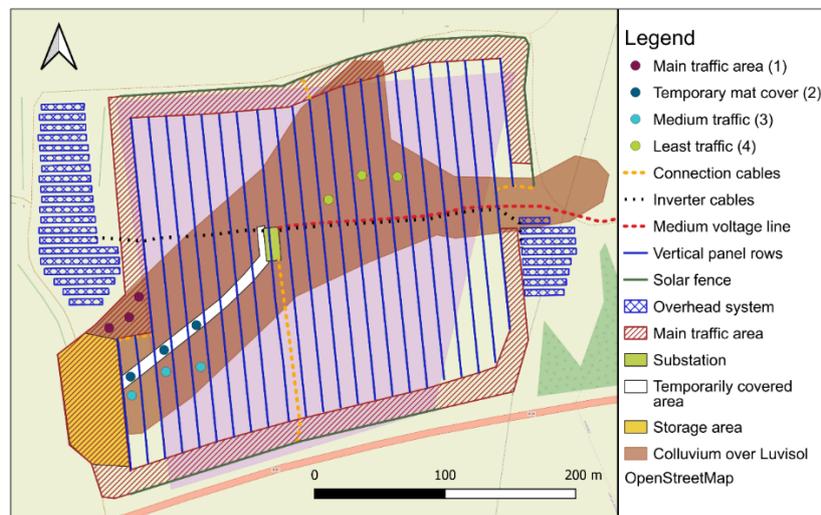


Figure 1. Schematic drawing of the examined case study site.

To estimate the effect of measured soil alterations on crop yield, wheat growth was simulated with the agroecosystem simulation package Expert-N (Version XN5.2) [20]. Simulation projects were setup for the four area categories with identical forcing (weather, field management) and input parameters, except the measured soil parameters including bulk density, saturated and residual water content, Van Genuchten α and n , and saturated hydraulic conductivity. Six consecutive years of wheat were simulated to account for annual variation, starting in fall 2014 until summer 2020, but the first year was excluded from the analysis due to unknown starting values for soil water parameters. The weather data at hourly resolution was retrieved from Solargis for Breitnau, 23 km from the case study site.

3. Results

3.1. Vehicle traffic

Material delivery and ramming issues caused delays and inconsistent progress, leading to extra traffic throughout the system, which needs to be considered when interpreting the findings. Generally, traffic was highest in the perimeters of the PV system and increased towards the storage area (Figure 2). The grid was further divided into areas of interest (Figure 3), and it was slightly adapted to better cover the main traffic areas (Grid 2). The southern main traffic lane (MTL) and the concrete street were additionally passed to access the overhead systems. With every PV row closer to the storage area, traffic increased on average by 68 passes on the southern and 30 passes on the northern MTL. The PV interspaces north of the cable trenches experienced on average 20 passes less (89) than the southern ones (110). Around the substation, cable trenches, and temporary mat cover, the soil was trafficked slightly more (132 – 152). After laying the grid connection line at 80 cm depth, the above soil surface was crossed multiple times when installing the PV system, which might have further disturbed the soil structure.

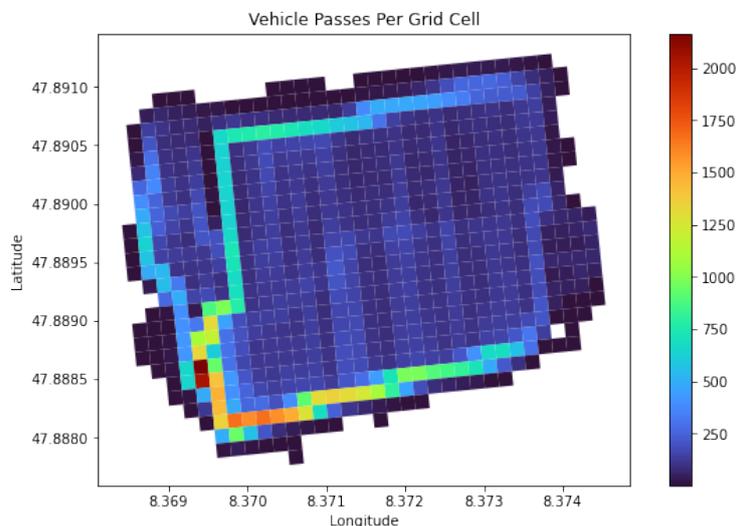


Figure 2. Number of passes per grid cell, being highest in the perimeters of the agrivoltaic systems and increasing towards the storage area.

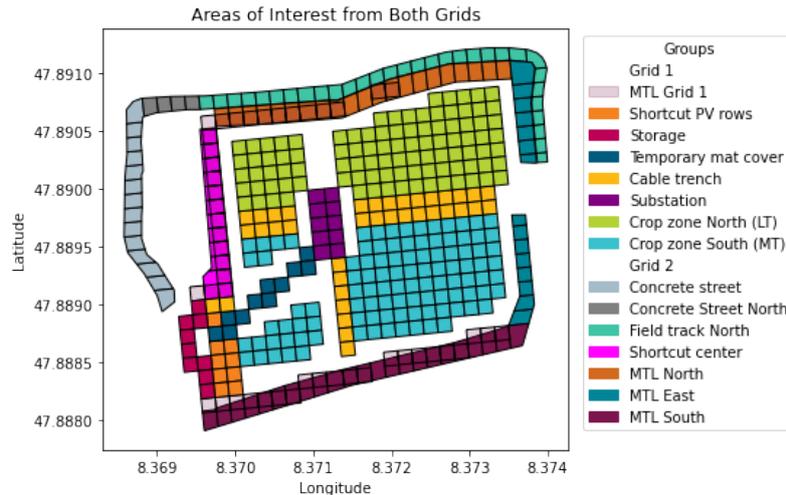


Figure 3. Grid categorization into areas of interest (typically 13.5 x 13.5 m) with adaptations to better cover the main traffic area (Grid 2).

In the soil protection concept, existing tracks were designated to access the northern area. However, tracking data showed that workers created a shortcut from the ends of the PV rows to the storage area through the center of the site, despite of efforts to recommunicate the designated paths and barrier tape. 'Shortcut center' was trafficked on average 700 times, while the official way was passed only 70 times (Concrete Street North). Similarly, MTL North was exposed to 560 passes, while the already existing gravel path, 5 m away, was only passed 30 times. Of all vehicles, the three loaders were accountable for 94% of the traffic, of which the wheel loader accounts for 55%, the telescopic loader for 31%, and the delta loader for only 8%. However, these numbers coincide with the tracking length, suggesting that the manually added vehicle traffic might have been underestimated.

In November, turf damage and tire ruts were visible throughout the site but especially on the main traffic lanes, and around the substation and cable trenches. Additionally, the scissor platform was driven on wet soil, probably during string cabling on one or two days, leaving tire imprints of about 15 cm depth next to many PV rows.

3.2. Soil assessments

In areas with highest traffic intensities and temporary mat coverage (TMC), the soil surface silted up, correlating with higher PR between 5 and 20 cm depth with a peak at 7 cm depth (3.0 - 3.25 MPa) compared to the less trafficked (LT) and medium trafficked (MT) areas (Figure 4). MTL shows significantly higher PR throughout the entire profile compared to the LT category (one-tailed Mann-Whitney-U test, p-value < 0.001). At 5 – 35 cm depth, all categories were significantly different from the LT category (p-values ≤ 0.001). However, from 35 – 65 cm depth, only MTL remained significantly higher (p-value = 0.008). At deeper depths, penetration was not always successful, with a notable increase of missing values for the MTL and TMC category. Unsuccessful penetrations might be due to dense layers which exceed the force of the measuring person or due to the presence of stones. In the first case, missing data conceal compaction effects in deeper layers, but at this site, both explanations are reasonable.

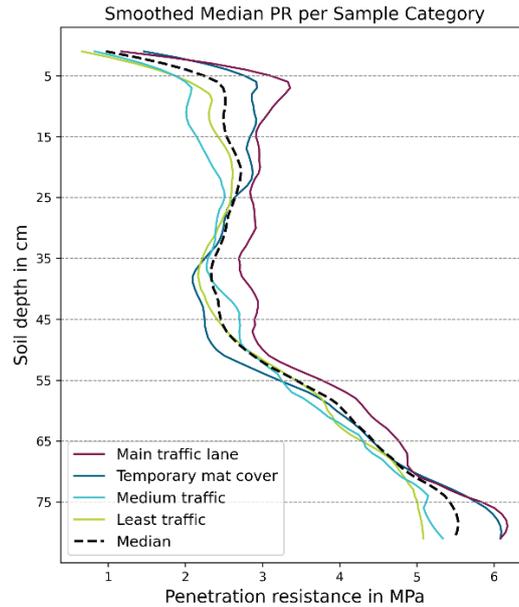


Figure 4. Median soil penetration resistance profile for each sample category and overall median of all measurements.

The mean BD of all 19 samples was $1.52 \pm 0.06 \text{ g/cm}^3$, showing no significant difference between depths or varying traffic intensities, which might be due to the small sample size. Concerning hydraulic properties, compaction generally leads to a lower saturated water content θ_s , higher residual water content θ_r , higher air entry value, a more moderate slope of the water retention curve, and a lower saturated hydraulic conductivity K_{sat} [1], [21]. At both depths, the water retention curves of MTL visibly differ from the mean (Figure 5). At 10 cm depth, MTL shows higher water contents at all tensions, which indicates compaction, even though the observed higher θ_s is contradictory to the expectations. At 50 cm, MTL has the lowest θ_s and generally lower water contents before the wilting point, but a high θ_r in comparison to the other categories, indicating a reduction in total porosity and a higher share of micropores.

From the water retention curve, the plant-available water capacity can be derived, which is the water content at pF 1.8 minus the dead water content at pF 4.2. The plant-available water capacity is lower in the topsoil than in the subsoil for all samples, except TMC. It is lowest for MTL with 11.4% in the topsoil and 13.9% in the subsoil, compared to the highest value of 17.0% at 10 cm depth in TMC and 16.5% in LT at 50 cm depth. The reduction of the plant-available water capacity in MTL indicates that the plants might be exposed to more water stress. However, since there was no soil evaluation prior to the construction, it cannot be excluded that soil was inhomogeneous before the construction.

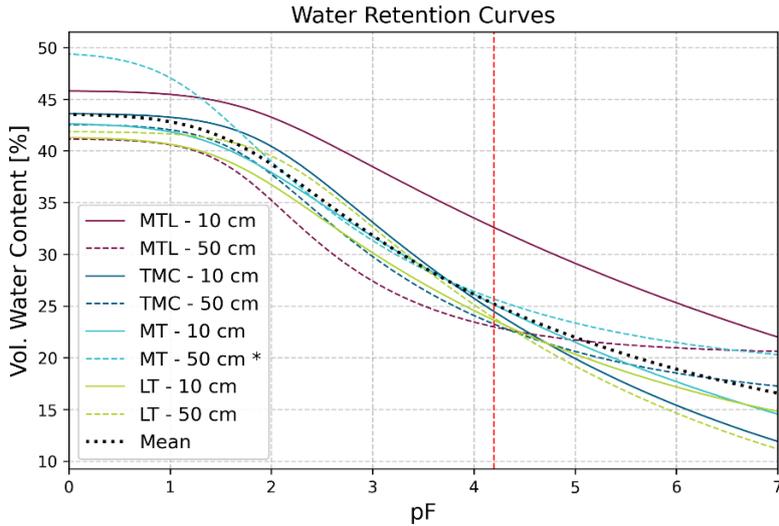


Figure 5. Average water retention curves per sample categories and depths and red dotted line at pF 4.2 (* only one sample, high θ_s is likely a measurement error).

3.3. Wheat simulation

The simulated grain yields are highest in 2016, which was coldest and wettest during the main growing period, and in 2020, which was warm and the driest year (Figure 6). Except for 2016, the yield is generally lower than the regional averages [22], but it might be that 2016 was still influenced by inaccurate starting values or that sufficient water availability mitigated compaction effects. The yield in the main traffic area drastically declines in comparison to the other categories, being 11% lower in 2016, 26% in 2017, and around 20% in the following years. The differences between the other three categories are rather minor, with the biggest differences of around 6% between TMC and MT in 2018. The average yield decline over all five years of MTL in comparison to LT is 18.8% and 20.1% compared to MT.

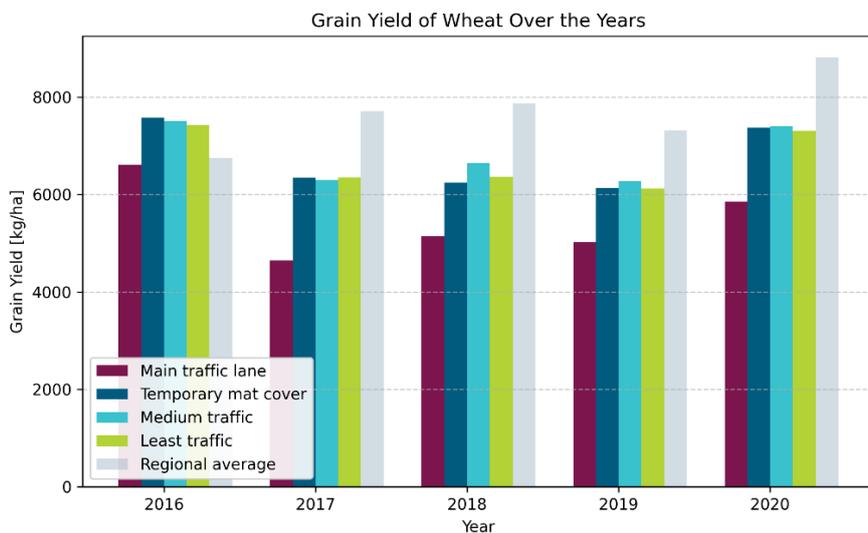


Figure 6. Comparison of simulated wheat yield of the different area categories and the regional averages from 2016 to 2020.

A comparison of the simulated biomass showed that the root biomass is slightly higher for MTL than the other categories in some years, and that the development of above-ground biomass is reduced from the beginning of the flowering stage in July onwards, being most pronounced in stem, straw and grains, but less in leaves. Simulations of soil water dynamics and

the relative reduction in actual transpiration T_{act} compared to potential transpiration T_{pot} (Figure 7) indicate that the plants suffer from water stress and need to put more effort into extracting water in the first 30 cm, especially in June and July, eventually explaining the reduced growth of above-ground biomass.

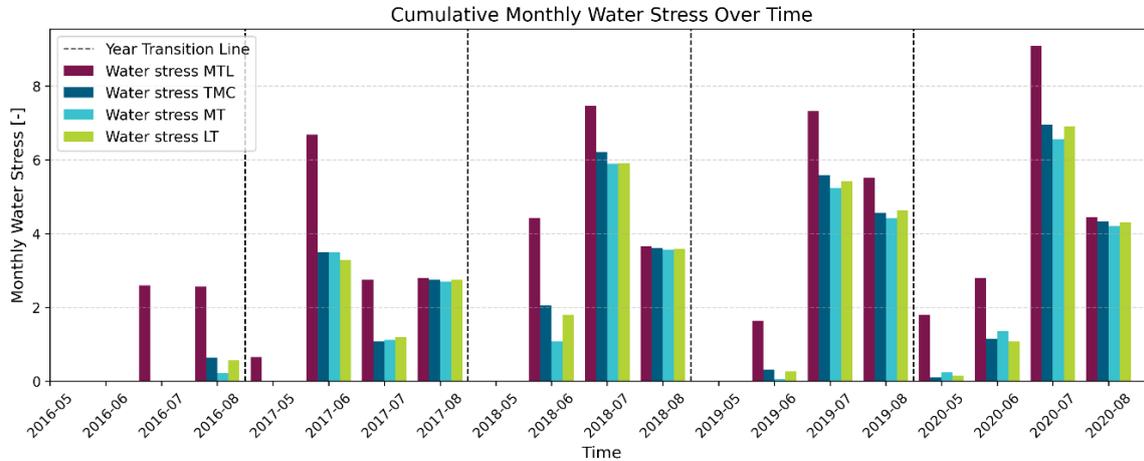


Figure 7. Cumulative monthly sum of water stress $(-1) * (T_{act}/T_{pot} - 1)$, where T_{pot} (mm) denotes the potential daily transpiration on a wet soil under the prevailing atmospheric conditions (saturation deficit, net radiation, wind, temperature) and T_{act} (mm) is the actual daily transpiration under the given soil moisture deficit ($T_{act} \leq T_{pot}$).

Soil evaluations were conducted before any soil management, hence this analysis does not consider regenerative processes or offer estimates for long-term impacts. Additionally, a grassland was established on the site, and its root system could have alleviated compaction effects, making the findings potentially non-comparable with projects on frequently tilled land.

3.4 Extrapolated yield reductions for entire vertical system

Since the main traffic area is a comparably small part of the site, the simulated yields were used to estimate the yield reduction for the vertical system and its perimeters based on the spatial share of the four assessed categories. About 5.78% of the area is not usable for agriculture because it is closer than 0.5 m to the PV rows, reducing the cultivable area from 9.43 to 8.89 ha. The yield predicted for MTL was assumed for the mainly trafficked areas, the storage area, the area around the substation, and the area ± 3 m to the cable trenches, which together add up to 2.64% of the total area. For TMC, LT, and MT, their respective simulated yields were taken. Thus, assuming that the entire area without an agrivoltaic construction can achieve yields as simulated for LT or MT, the yield loss due to soil compaction (excluding land loss) would amount to 4.93% and 6.44% respectively.

4. Conclusion

This vehicle traffic analysis at a construction site of a vertical agrivoltaic system showed very high traffic intensities adjacent to the PV system on the shortest way to the storage area. While the number of passes is alarming, vehicles were generally light-weight and wheeled vehicles were replaced with smaller tracked ones in autumn. As implemented in this case study, soil protection concepts including traffic plans, protection of storage areas or areas exposed to heavy vehicles, and use of light-weight vehicles with a large tire-soil contact area are key measures of prevention. Additionally, this research showed that existing driving policies and stops at high soil moisture levels might need stricter reinforcement by financial implications or physical barriers. Ideally, the shortest path to the storage area would be via headlands or existing gravel tracks, however, security distances and fences frequently make this impractical.

Including protection and recultivation measures already in the financial calculations of projects can help with their successful implementation.

Soil assessments, such as those conducted in this study, help to capture soil damage and link it to potential future yield losses. Penetration resistance tests are a comparably easy and cheap method to assess compaction effects, but measurements are sensitive to water content of the soil and can rather be interpreted in relative than in absolute terms. Additionally, penetration resistance tests have their limits at very dense or stony soil layers. Analyses of hydraulic properties draw a more accurate picture on changes of pore structure and the plant-available water but require specialized equipment and are labour intensive.

Limitations to this study include site-specific additional traffic and vehicle tracking issues, which limit the generalizability of the traffic analysis. Additionally, measured changes in soil properties cannot be directly linked to vehicle traffic, because soil assessments prior to the construction were not feasible. Repeated assessments in the coming years would be necessary to better evaluate soil recovery and long-term yield decline. Despite these limitations, this case study offers an initial contribution to understanding the vehicle traffic required for the installation of a vertical agrivoltaic system and for the first time demonstrating its associated impacts on soil properties and wheat yield.

Data availability statement

The measured data presented in this study can be made available by the corresponding author upon reasonable request.

Underlying and related material

There is no other underlying and related material.

Author contributions

Jana Kalmbach: Conceptualization, Investigation, Formal analysis, Visualization, Writing – original draft, and Writing – review & editing. Sebastian Gayler: Supervision, Resources, Software (Expert-N). Rhea Pöter: Writing – review & editing.

Competing interests

The authors declare that they have no competing interests.

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