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НОВЫЕ МЕТОДЫ И РЕЗУЛЬТАТЫ ИССЛЕДОВАНИЙ ЛАНДШАФТОВ В ЕВРОПЕ, ЦЕНТРАЛЬНОЙ АЗИИ И СИБИРИ

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Chapter II/60: ANALYSIS AND MODELING OF FIELD TRAFFIC INTENSITY IN FARMING LANDSCAPES USING GIS

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ABSTRACT. Mitigating unnecessary field traffic at high wheel load and contact stresses and reducing traffic intensity of tillage and harvest operations as well are key measures to protect soil against harmful soil compaction and related negative effects on the various soil functions. This paper gives an example of the use of spatial information technology to predict soil compaction risks based on GPS data recorded by farm vehicles involved in tillage and harvesting processes. It introduces into a GIS model that connects GPS data, farm machinery data and yield information to map wheeling intensity and to spatially calculate wheel loads and mean contact area stresses, including their changes during silage maize harvest. The application of our model enables to detect within-field sections of high mechanical stresses applied by farm vehicles at high spatial resolution and supports to optimizing of field traffic strategies for tillage and harvest operations on individual fields.

Резюме. Сокращение движения на полях сельскохозяйственных машин с высокой нагрузкой на колеса и контактными напряжениями, а также снижение интенсивности движения при обработке почвы и уборке урожая являются ключевыми мерами защиты почвы от вредного уплотнения и связанных с ним отрицательных эффектов на различные функции почвы. Данная глава дает пример использования геоинформационных технологий для предсказания рисков уплотнения почвы на основе данных глобальной системы позиционирования (GPS), получаемых сельскохозяйственными машинами при обработке почвы и уборке урожая. Вводится модель ГИС, которая связывает данные GPS, данные о сельскохозяйственной технике и информацию об урожайности, позволяя строить карты интенсивности проходов техники и рассчитывать пространственное распределение нагрузки от колес и среднего напряжения для площади контакта с почвой, включая изменения этих показателей, во время уборки кукурузы на силос. Применение нашей модели позволяет с высоким пространственным разрешением определять участки полей с высокими механическими напряжениями от сельскохозяйственных машин и служит для оптимизации движения техники при обработке почвы и уборке урожая в пределах отдельных полей.
INTRODUCTION
Soil compaction in farmland soils is one of the main threads to soil productivity. Major concerns to sustain the various soil functions in arable soils are the increase in vehicle mass and the continuous growth of the loading weights of harvesters and trailers over the last decades on the one side, and increasing field traffic intensity on the other. Heavy machine weights, high wheel loads and intense field traffic are typical for the harvest of sugar beets and silage maize. To prevent of harmful soil compaction, especially through harvest traffic, optimization of field traffic is necessary. Recent research activities, such as the interdisciplinary project "SoilAssist", funded by the German Ministry of Education and Research (BMBF) within the "BonaRes" research initiative, aim at developing soil conserving field traffic strategies to reduce soil compaction.

Particularly under moist soil conditions that typically occur at harvest times for sugar beets and silage maize the risk of soil and subsoil compaction increases strongly, because the resisting forces in the soil are in imbalance with the external stresses applied by heavy field machinery (Nevens & Reheul [1], Peth et al. [2]). High wheel or axle loads of vehicles and harvesters and wheeling intensity (e.g. the number of wheel passes and repeated wheel-to-wheel passages) substantially increase the vulnerability of soils to irreversible soil deformation and subsoil compaction (Soane et al. [3], Hákansson & Reeder [4], Hamza &Anderson [5]). In contrast to easily recognizable phenomena of soil degradation such as soil erosion, soil compaction does not leave visible marks in a landscape. It is masked by other signals like reduced crop yields, delayed growth or ponding water, which makes it difficult to recognize and locate soil compaction directly (McGarry [6]).

Modern field trucks and harvesters are often equipped with GNSS (Global Navigation Satellite System) technology, like GPS or RTK-(real time kinematic) GPS today. Thus, a promising approach to spatially detect soil compaction risks caused by field traffic is to process the data collected from vehicle-mounted GPS-receivers using Geographical Information Systems (GIS). Yule et al. [7], Richards [8] and Kroulík et al. [9] applied GPS data to map vehicle movement and trafficking intensity. Duttmann et al. [10] used position data from vehicle-mounted GPS to evaluate on-road and in-field transportation effort during silage maize harvest and to simulate traffic-induced loads and contact stresses exerted to soils of harvested fields. Estimates of traffic intensities for selected field operations are given by Hákansson [11], suggesting that the wheel track area of harvesting operations such as sugar beet harvest solely vary between 120 and 180% relative to the field area.

However, studies that take the spatial distribution of traffic intensity and the within-field distribution of varying wheel loads and contact area stresses during harvests into account, are widely missing. This is also valid for calculations of the field area affected by certain wheel loads and mean ground contact stresses.

AIM OF THE METHOD
Our model aims at calculating traffic intensity through tillage and silage and harvest processes on single fields considering the position data recorded by farm vehicles, the characteristics of the individual farm machines and the changing loads of the trailers used for transporting the harvested goods (cf. Duttmann et al. [10,12], Duttmann et al. [13]). In detail our GIS-based model enables:
- the mapping of traffic patterns based on real traffic operations and machine characteristics at high spatial resolution,
- the calculation of percentages of the trafficked field area during harvest and other farm operations,
- the estimation of maximum wheel loads and maximum mean contact stresses applied by farm vehicles and harvesters at any location inside a field, considering the changes in wheel load and contact stress of tractors and trailers during loading at harvesting processes,
- the identification of repeatedly wheeled track sections and the calculation of the area percentages of multiple wheel-to-wheel passages and
- the spatial detection of "hot spots" of traffic intensity inside a field or ensembles of fields.
To run the model, GPS-data collected by the individual vehicles involved in farm operations are required. Besides, the model necessitates the technical characteristics of the single vehicles used for tillage and harvesting such as (e.g. mass, axle widths, tire sizes, tire inflation pressure, cutter head widths of harvesters, storage capacity of trailers) as input variables. The vehicle data are taken from a machine data base connected with the model. In this paper the application of our model will be exemplarily demonstrated for silage maize harvest, while the model is also applicable to cereal and sugar beet harvests. In this case example a self-propelled forage harvester with a 4.5 m wide cutter head and three transportation teams consisting of a tractor and a tandem axle trailer were used. To verify the modeled changes in wheel loads and contact area stresses calculated for the loading section by real data, the tare weights and loading weights of the transport vehicles were measured before and after a single loading sequence. For recording all traffic activities inside the field, every transport and harvesting vehicle was equipped with a GPS receiver. The receiver antennas were mounted above the center of the tractors’ rear axles and the harvesters’ front axles in order to exactly construct the wheel tracks in subsequent modeling. The positions of the certain vehicles were automatically recorded every second. To manage and process the received GPS data during the field campaign we used the mobile GIS ArcPad (ESRI), whereas the later modeling of field traffic was performed by using ArcGIS, Vers. 10.1.3 (ESRI).

**Figure 1** – Modeling scheme to spatially simulate traffic activities inside of a field (according to Duttmann et al. [12], p. 103; simplified)
MODELING OF FIELD TRAFFIC AND FIELD TRAFFIC INTENSITY

To model the courses and sizes of the wheel tracks the GPS position data of tractors and the harvester were converted into lines, where the length of each line segment corresponded to a time interval of 1 second. Every line segment relates to a database record that stores the xy-coordinate and time signal data of the segments’ starting and ending points for each vehicle and “field-cycle”. A “field cycle” consists of three sections: (1.) the transfer of the unloaded transport vehicles from the field-border to the position of the harvester, (2.) the harvesting and loading section and, (3.) the return passage of the loaded vehicles to the field border. The major steps of data processing are shown in Figure 1. A more detailed description of the modeling procedure is given by Duttmann et al. [10,12].

The mean ground contact areas of the driving tires of the harvester and the tractors were measured under field conditions with a hydraulic tire-measuring device, while the contact areas of the other tires (front tires of the tractors, rear tires of the harvester, trailer tires) were estimated according to Diserens [14] and Diserens [15] for cross-ply tires and semi-firm soils. The changing loading weights were calculated by interpolating between the tare weight of the trailers at the start of the loading process and gross weight at the end of a cycle, assuming a constant speed.

![Figure 2](image)

**Figure 2** – Wheel track patterns and spatial distribution of maximum wheel loads applied at least once to a wheel track during silage maize harvest (Duttmann et al. [12], p. 105; slightly modified)

RESULTS

A selection of feasible modeling results is presented in Figure 2. It shows the spatial patterns of field traffic during a silage maize harvest and the maximum wheel loads applied to soil at every position inside a field. To assess field traffic intensity, we exemplarily used the percentage of the wheeled area related to the field area and the number of repeated wheel-to-wheel passages as indicators. As demonstrated in Figure 2a, the modeled wheel track patterns for load and harvest activities give a clear spatial indication of those field sections that are mainly affected by multiple wheeling. In this case, the headlands and the entrance areas and the routes from the field entrance to the opposite side from where the unloaded transport vehicles approach the actual position of the harvester were found to be the locations of highest wheeling density and highest numbers wheel-to-wheel passages. Calculations also show that at least 12% of the...
complete field have been wheeled more than six times. Repeated wheeling at the same or a higher load increases the risk of soil compaction. Besides, wheel loads > 50 kN are assumed to have high impact on subsoil compaction (van den Akker et al. [16]). The spatial distribution of maximum wheel loads applied to a wheel track is shown Figure 2b. It reveals that nearly 44% of the field area was wheeled at least once with a wheel load > 50 kN, which equals to 70% of the total wheel track area. In addition to the headlands and the entrance areas, track sections of highest wheel loads where detected for the return routes of the fully loaded transporters. Considering the comparably long distances (median distance 175 m) the loaded transport vehicles had to cover when returning to the field gate, it is obvious that a major share of load input could be avoided. Possible measures could be either to optimize field traffic, e.g. by implementing a controlled traffic farming system (CTF), or by adjusting the field geometry such that the harvest distance in one-way direction equals to the loading capacity of the trailer. The model presented here supports to finding optimal traffic strategies for given field conditions, accounting for the farm-specific tillage and harvest practices applied for various crop types and crop rotations in order to reduce soil compaction risks.

CONCLUSIONS
1. Spatial analyses of field traffic using geodata such as GNSS data collected by farm vehicles supports to the detection of soil compaction risks resulting from vehicle load inputs.
2. Combining the recorded position data with the technical properties of the individual farm vehicles enables the calculation of varying wheel loads and ground contact stresses at a high level of precision. Thus, it is possible to compare the external load applied by farm machinery against the load bearing capacity of the soils to deduce recommendations of the allowable load inputs under given soil conditions.
3. Our model assists to sampling strategies for soil compaction monitoring at the field and landscape scales, because it allows to exactly quantify the mechanical impact of farm machinery at every position inside of a trafficked field, facilitating the selection of relevant measurement sites.

REFERENCES
Abstract. A new criterion has been developed for limiting the compacting effect of machinery on soil. Its essence lies in the fact that, in accordance with the Russian state standard, the permissible pressure of agricultural aggregates on the soil is expressed through the harmful intensity of the mechanical impact on it during field work. The new criterion is more accessible in practical use. In addition to the normal load on the soil, it takes into account the strength relationship between the energy source and the machine it aggregates, which affects the sealing properties of the propulsions, and therefore more adequately represents the process under study in the agrolandscape. The required parameters of the evaluation are obtained without experiments - according to a priori data of the technical characteristics of the aggregate and the properties of the soil on which the field works are carried out. The use of this criterion allows identifying in advance the environmentally friendly operating conditions of any field agricultural unit. The adequacy of the innovation criterion has been confirmed experimentally.

Keywords: agrolandscape, agricultural aggregate, soil density, contact surface pressure, harmful influence, gauge depth.