学位論文内容の要旨

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学位論文題名

Development of a soil compaction management system: Using hyperspectral-based soil properties sensing

（土壌踏圧管理システムの開発：ハイパースペクトルベース土壌センシング）

This thesis explores precision tillage (PT) as a site-specific alternative to conventional tillage practices for addressing soil compaction (SC) while minimizing environmental impacts. A two-step approach was adopted for this research: first, evaluating hyperspectral camera (HSC) technology as a non-invasive method for characterizing SC properties, then developing a data processing workflow to convert HSC data into practical PT mapping plans. HSC performance is validated against established bulk density (BD) and packing density (PD) measurement ranges for PT. Additionally, a field-based controlled experiment was conducted to assess the impact of varying SC levels on wheat growth, as a result, an optimal compaction range for maximizing yield was identified. The outcomes inform the development of a wheat-specific PT framework.

1. Development of remote sensing methodology for soil compaction assessment

This study explores the use of remote sensing to rapidly measure key soil parameters for PT implementation. This was achieved by combining conventional soil property measurements with a non-contact approach using in-field HSC data acquisition. Six methods were generated and divided into two sets to determine soil properties to make PT decisions. The first set includes mathematical functions that were generated from the ground true data (GTD). The second set includes functions that were generated from the remotely sensed HSC data and have a relationship with the methods in the first set. It was possible to optimize the functions' parameters to increase the accuracy. In addition, prediction error categories set at 5% intervals were used to select the best method. The results show that an optimized method based on the GTD has an overall error below 5%, and an optimized method based on HSC data has an overall error of about 10%. These findings were successfully translated into spatial mapping outputs that provide actionable precision tillage recommendations, creating a seamless pathway from remote sensing data collection to practical field application.

2. Quantification of soil compaction effects on wheat productivity

This section investigates site-specific SC by varying the BD of subplots as a means of evaluating PT relevance within the framework of PA. To evaluate the effects of different soil SC levels on wheat (*Triticum aestivum* L.) growth, yield and nutrient use efficiency, four distinct compaction treatments and a control were established in the field. Unlike computer simulations, these field trials capture actual soil-load responses. Initial BD were set by applying 1-4 passes of a 400 kg vibratory plate compactor, resulting in BD1 = 1.30 Mg/m^3, BD2 =1.25 Mg/m^3, BD3 = 1.24 Mg/m^3, BD4 = 1.19 Mg/m^3, and a Control subplot at 1.17 Mg/m^3. This helped determine the BD impact on soil physical properties, soil chemical properties, crop development data and nutrient access/uptake, and the subsequent effect on yield. The results obtained indicate that a moderate SC (BD = 1.24 Mg/m^3) optimized wheat nutrient utilization, producing higher yields than highly compacted or loose soil. The best subplot's yield was 173.6% greater than that of the hardest subplot. The Control subplot recorded a yield that is 143.4% greater than the hardest subplot. Spatial analysis showed SC affects multiple nutrient pathways simultaneously. A combined P-Ca-Mg model explained 97.2% of yield variation (R^2 = 0.972, RMSE = 0.1053 ton/ha), outperforming single-nutrient models by 14%. The spatial analysis results revealed a non-linear relationship between compaction level and yield. Importantly, a moderate SC level was identified as optimal for wheat productivity, providing strong evidence for the relevance of PT strategies tailored to site-specific soil conditions.

3. Integration of findings into the precision agriculture framework

Insights from wheat responses to varying SC levels were synthesized to develop a wheat-specific PT plan. The experimentally identified optimum SC level (BD = 1.24 Mg/m^3) serves as the foundation for PT recommendations aimed at maximizing yield. Soil nutrient management maps generated during critical wheat growth stages provide spatial precision for subsequent fertilization planning. Additionally, the hyperspectral (HS) imaging methodology enabled the development of a streamlined workflow for rapid assessment of SC effects, facilitating timely and targeted interventions. This integration creates a comprehensive framework that connects remote sensing capabilities with agronomic understanding to deliver practical, site-specific management solutions for wheat producers managing soil compaction.