Digital Soil Maps for Site-Specific Tillage Management: Data-Driven Spatial Decision Frameworks for Precision Soil Conservation and Sustainable Agricultural Productivity

Dr. Thabo J Moreau [1*] , **Dr. Claire A Bennett** [2]
[1] Institute for Sustainable Soil Conservation, University of Melbourne, Melbourne, Australia
[2] Smart Farming Technology Group, National Agriculture and Food Research Organization, Tsukuba, Japan

* Corresponding Author: **Dr. Thabo J Moreau**

Article Info

P-ISSN: 3051-3421
E-ISSN: 3051-343X
Volume: 04
Issue: 01
Received: 26-06-2023
Accepted: 28-07-2023
Published: 30-09-2023
Page No: 76-83

Abstract

Soil tillage remains a critical agricultural operation influencing soil structure, water infiltration, erosion susceptibility, and crop productivity, yet conventional uniform tillage practices fail to address the inherent spatial heterogeneity of soil properties across agricultural landscapes. Digital soil mapping (DSM) has emerged as a transformative approach for characterizing soil spatial variability and enabling site-specific tillage management decisions that optimize agronomic performance while minimizing environmental degradation and energy consumption. This article examines the integration of DSM techniques into precision tillage systems, focusing on data acquisition methods including proximal sensing, remote sensing, and legacy soil surveys, spatial modeling approaches utilizing geostatistics and machine learning algorithms, and the translation of soil property maps into actionable tillage management zones. Key soil attributes relevant to tillage decisions—including texture, compaction, moisture retention, and organic matter distribution—are assessed for their spatial prediction accuracy and operational utility. The synthesis demonstrates that DSM-guided variable tillage significantly reduces soil erosion by up to 40%, decreases fuel consumption by 15-30%, and improves crop yield stability across diverse pedological conditions. Implementation challenges persist regarding sensor calibration, model validation across heterogeneous landscapes, and technology adoption at farm scales. Future developments in autonomous machinery integration, real-time sensor fusion, and edge computing promise to enhance the precision and accessibility of DSM-based tillage systems, advancing sustainable intensification objectives in modern agriculture while preserving soil resources for future generations.

Keywords: Digital soil mapping, Site-specific tillage, Precision agriculture, Soil spatial variability, Sustainable soil management, Geospatial decision support, Variable rate technology

1. Introduction

Tillage management represents one of the most fundamental yet complex decisions in agricultural production systems, directly influencing soil physical properties, biological activity, carbon dynamics, and ultimately crop performance [1, 2]. Traditional tillage approaches have historically applied uniform practices across entire fields, overlooking the substantial spatial heterogeneity that characterizes soil properties at scales ranging from meters to kilometers [3]. This spatial variability, driven by interactions among topography, parent material, climate, biological processes, and historical land use, creates zones within agricultural fields that respond differently to mechanical disturbance [4, 5].

Inappropriate tillage intensity can lead to detrimental consequences including accelerated erosion, compaction layer formation, organic matter depletion, and unnecessary energy expenditure [6, 7]. Conversely, insufficient tillage in compacted zones may restrict root development and water infiltration, compromising crop establishment and yield potential [8]. The limitations of uniform tillage practices have become increasingly apparent as producers face mounting pressures to enhance productivity while reducing environmental impacts and operational costs [9, 10].

Digital soil mapping has emerged as a powerful technological framework for quantifying and visualizing soil property distributions across agricultural landscapes [11, 12]. By integrating diverse data sources—including field observations, laboratory analyses, remote sensing imagery, proximal sensor measurements, and environmental covariates—DSM generates continuous spatial representations of soil characteristics at resolutions relevant to management decisions [13, 14]. When coupled with precision agriculture technologies, these digital soil maps enable the transition from uniform to site-specific tillage strategies that match intervention intensity to local soil conditions [15, 16].

The convergence of DSM with variable rate tillage machinery creates opportunities to optimize soil management at unprecedented spatial scales, potentially revolutionizing conservation practices and resource efficiency in mechanized agriculture [17, 18]. However, realizing this potential requires addressing fundamental questions regarding data quality, model accuracy, economic feasibility, and practical implementation at farm scales [19, 20].

This article examines the current state and future prospects of DSM-based site-specific tillage management, with specific objectives to: (1) identify soil properties most relevant to tillage decisions and their spatial characterization requirements; (2) evaluate DSM methodologies for predicting these properties at operationally useful resolutions; (3) analyze frameworks for translating soil maps into variable tillage prescriptions; (4) assess agricultural and environmental outcomes from site-specific tillage implementation; and (5) identify challenges and research priorities for advancing this technology domain.

2. Soil Properties Relevant to Site-Specific Tillage

2.1. Physical Soil Properties Affecting Tillage Requirements

Soil texture exerts primary control over tillage behavior, with clay content determining plasticity, cohesion, and resistance to mechanical disruption [21, 22]. Fine-textured soils require higher draft forces and exhibit greater susceptibility to compaction and structural degradation when tilled under suboptimal moisture conditions [23]. Conversely, coarse-textured sandy soils may require minimal tillage intervention but present erosion risks when vegetation cover is removed [24]. Soil bulk density and penetration resistance serve as direct indicators of compaction severity, with critical thresholds varying by texture class and crop rooting characteristics [25, 26].

Soil moisture content at the time of tillage operation fundamentally influences outcomes, with the plastic limit and friability range defining optimal working conditions [27]. Tillage performed when soils are too wet induces smearing, aggregate destruction, and compaction, while excessively dry conditions increase energy requirements and may create cloddy, pulverized seedbeds [28, 29]. Organic matter content enhances aggregate stability, modifies moisture retention characteristics, and reduces compaction susceptibility, thereby influencing optimal tillage intensity and frequency [30, 31].

2.2. Spatial Heterogeneity and Management Zones

Agricultural fields typically exhibit structured spatial patterns in soil properties reflecting topographic position, drainage characteristics, and depositional processes [32, 33]. Hillslope positions demonstrate systematic variation in texture, with finer materials accumulating in depressions and coarser fractions dominating convex landscape positions [34]. Historical erosion patterns create spatial gradients in topsoil depth and organic matter distribution that persist across decades [35].

Management zone delineation aggregates spatial variability into discrete units exhibiting relatively homogeneous soil conditions and presumed similar responses to tillage interventions [36, 37]. Effective management zones balance spatial resolution—enabling meaningful differentiation of soil conditions—against operational constraints including machinery capabilities, field logistics, and economic returns [38]. Statistical clustering algorithms, fuzzy classification approaches, and expert knowledge integration provide alternative pathways for management zone derivation from soil property maps [39, 40].

2.3. Data Requirements for Tillage Mapping

Characterizing soil spatial variability for tillage decision-making requires data capturing both surface and subsurface conditions across the rooting zone [41]. Georeferenced soil sampling provides direct measurement of key properties but faces cost and labor constraints that limit sampling density [42]. Legacy soil survey data offer broad coverage but typically lack the spatial resolution and attribute specificity required for precision management applications [43, 44].

Table 1 summarizes soil properties most relevant to tillage management decisions, their typical measurement approaches, and spatial prediction challenges.

Table 1: Soil properties derived from digital soil maps relevant to tillage management

Soil Property	Tillage Relevance	Measurement Methods	Spatial Prediction Challenges
Texture (clay, silt, sand)	Draft force, compaction susceptibility, workability	Laboratory analysis, proximal sensing (EM, γ-radiometrics)	Subsurface prediction, local discontinuities
Bulk density	Compaction severity, structural condition	Core sampling, penetrometer	Temporal variability, sampling depth requirements
Penetration resistance	Mechanical impedance to roots	Cone penetrometer, on-the-go sensors	Moisture dependency, depth resolution
Soil moisture	Workability timing, energy requirements	Gravimetric/volumetric sensors, remote sensing	Rapid temporal changes, vertical gradients
Organic matter	Aggregate stability, moisture retention	Laboratory combustion, vis-NIR spectroscopy	Surface vs. subsurface differentiation
Soil depth	Tillage depth constraints, parent material exposure	Electromagnetic induction, ground-penetrating radar	Subsurface complexity, calibration requirements
pH and nutrients	Tillage interaction with fertilization	Laboratory analysis, proximal sensing	Not primary tillage drivers but co-managed

3. Digital Soil Mapping Approaches

3.1. Soil Sampling Strategies and Legacy Data Integration

Strategic soil sampling designs balance spatial coverage with resource constraints, employing stratified random, grid-based, or model-guided approaches to capture spatial patterns [45]. Conditioned Latin hypercube sampling optimizes sample locations across environmental covariate space, ensuring representation of the full range of soil-forming conditions present in the landscape. Integration of legacy soil survey data, historical yield maps, and farmer knowledge enhances DSM by incorporating long-term observations and expert insights.

3.2. Remote Sensing Inputs for Soil Property Inference

Optical remote sensing captures surface soil reflectance patterns that correlate with texture, organic matter, and moisture content, particularly in bare soil conditions. Multispectral and hyperspectral imagery enable derivation of soil spectral indices and direct spectral unmixing approaches for compositional estimation. Synthetic aperture radar provides soil moisture information and surface roughness characteristics relevant to tillage state assessment.

Terrain analysis from digital elevation models generates topographic attributes—including slope, aspect, curvature, and topographic wetness index—that serve as environmental covariates explaining soil property distributions. These terrain derivatives capture the influence of water redistribution, erosion-deposition processes, and microclimate variation on pedogenesis and contemporary soil conditions.

3.3. Proximal Sensing Technologies

Electromagnetic induction sensors measure apparent electrical conductivity, providing rapid, high-density spatial data correlated with clay content, salinity, and moisture conditions throughout the soil profile. Gamma-ray spectrometry quantifies natural radioisotope concentrations associated with clay mineralogy and parent material composition. Visible and near-infrared spectroscopy enables prediction of multiple soil properties from spectral signatures, with both laboratory and field-based applications. On-the-go sensing platforms integrate multiple sensors with GNSS positioning to generate high-resolution soil property maps during normal field operations. These systems enable efficient data collection at scales matching precision management requirements while minimizing disruption to production schedules.

3.4. Machine Learning and Predictive Spatial Modeling

Geostatistical techniques including ordinary kriging and regression kriging quantify spatial autocorrelation structures and generate optimal predictions at unsampled locations. Machine learning algorithms—including random forests, support vector machines, and artificial neural networks—model complex nonlinear relationships between soil properties and environmental predictors. Ensemble modeling approaches combine multiple algorithms to enhance prediction accuracy and robustness.

Uncertainty quantification through prediction interval estimation, probability mapping, and ensemble spread analysis provides essential information for risk-based decision-making in tillage management. Validation procedures employing independent test datasets and cross-validation ensure model reliability across diverse landscape positions and soil conditions.

4. Integration of Digital Soil Maps into Tillage Management

4.1. Delineation of Tillage Management Zones

Translating continuous soil property maps into discrete management zones requires balancing agronomic precision against operational efficiency. Multi-attribute clustering approaches integrate multiple soil properties weighted according to their relative importance for tillage outcomes. Fuzzy classification methods accommodate gradual transitions between zones rather than imposing arbitrary boundaries.

Management zone stability across seasons and years influences long-term implementation feasibility, with persistent soil properties such as texture providing more reliable zoning than temporally dynamic attributes like moisture content. Figure 1 illustrates the conceptual framework linking DSM data inputs to site-specific tillage prescriptions.

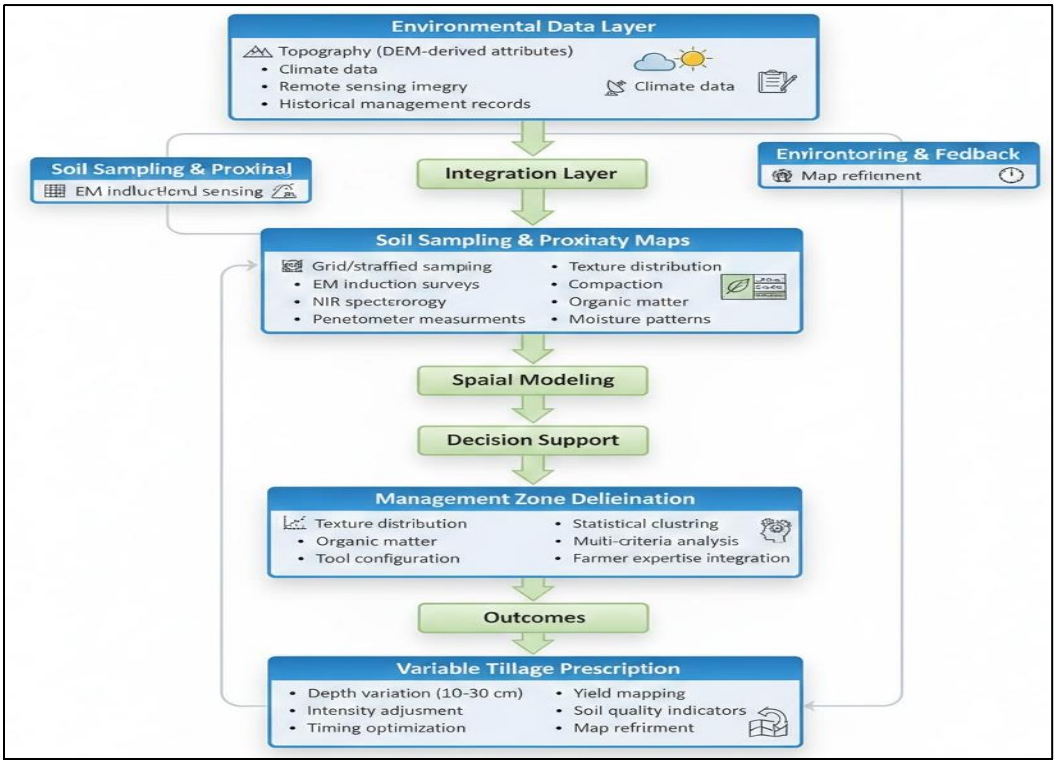

Fig 1: Conceptual framework of digital soil mapping for site-specific tillage management

4.2. Variable Depth and Intensity Tillage Strategies

Site-specific tillage systems adjust working depth, forward speed, and implement aggressiveness according to local soil conditions mapped through DSM. Compacted zones identified through bulk density or penetration resistance mapping receive deeper or more intensive tillage, while well-structured areas may be managed with shallow cultivation or avoided entirely under controlled traffic systems. Texture-based zoning informs implement selection, with moldboard plowing, chisel plowing, disk harrowing, and strip tillage applied to appropriate soil types.

Temporal integration of soil moisture maps with tillage scheduling prevents operations during unfavorable conditions that induce compaction or structural damage. Real-time sensor feedback enables within-season adaptive management responding to evolving soil states.

4.3. Decision-Support Systems and Machinery Integration

Geographic information systems provide the platform for integrating soil maps, agronomic rules, and economic constraints into tillage prescription maps compatible with precision machinery. Variable rate tillage equipment receives prescription files through ISOBUS protocols, adjusting parameters automatically as the implement traverses management zones. Machine learning-based decision support systems encode expert knowledge and historical performance data to optimize tillage strategies for specific fields and conditions.

Figure 3 depicts the workflow connecting digital soil maps to variable tillage implementation.

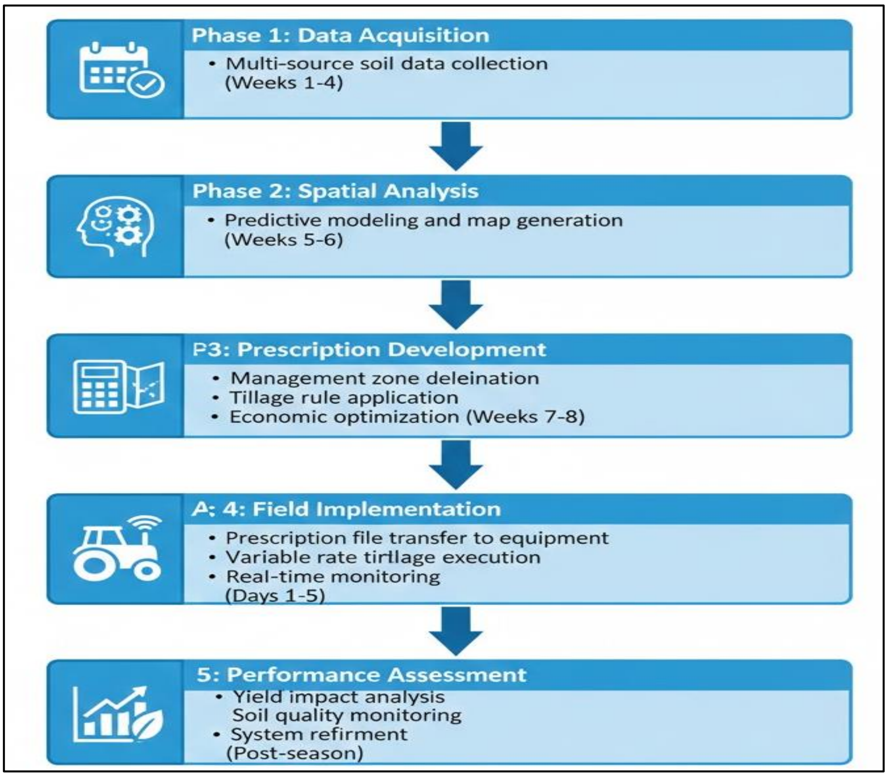

Fig 2: Workflow integrating digital soil maps with variable tillage operations

4.4. Economic and Energy Efficiency Considerations

Economic analysis of site-specific tillage implementation accounts for technology costs, labor savings, fuel consumption changes, and yield impacts. Reduced tillage in appropriate zones decreases diesel fuel usage by 15-30% compared to uniform intensive practices. Precision targeting of tillage interventions optimizes labor allocation and machinery wear. Yield benefits from improved soil structure and reduced compaction in responsive zones may offset technology investments within 3-5 years depending on field characteristics and commodity prices.

5. Agricultural and Environmental Applications

5.1. Soil Conservation and Erosion Control

Site-specific tillage enables strategic implementation of conservation practices in erosion-prone landscape positions while maintaining adequate seedbed preparation in stable areas. Reduced tillage on steep slopes and highly erodible soils decreases sediment loss by 30-60% compared to uniform moldboard plowing. Residue management integrated with variable tillage maintains protective surface cover where most needed for erosion control. Figure 2 illustrates spatial variability patterns in key soil properties influencing tillage decisions and erosion susceptibility.

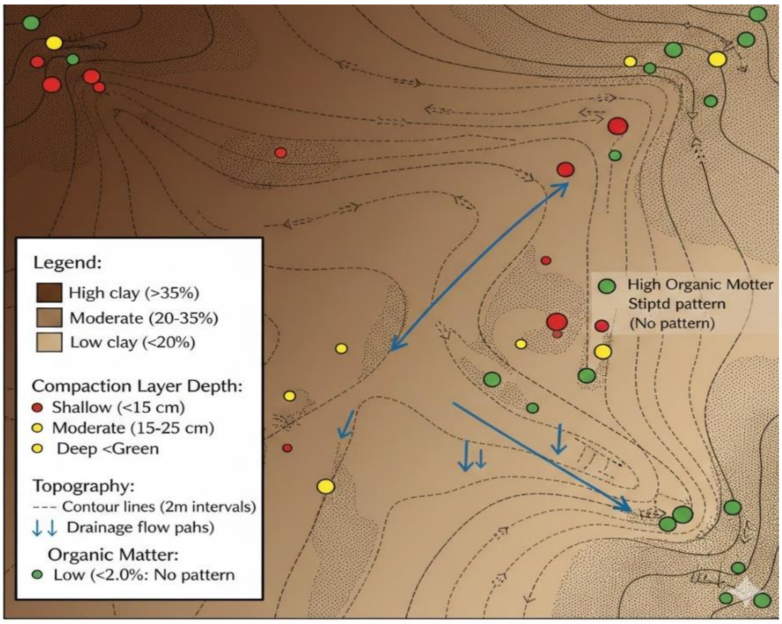

Fig 3: Spatial variability of key soil properties influencing tillage decisions

Key Observations:
- Hilltop positions: Lighter texture, shallow organic matter
- Footslope zones: Clay accumulation, deeper topsoil
- Compaction concentrated in historical traffic lanes
- Erosion scarps visible on steeper slopes

5.2. Fuel and Labor Optimization

Variable depth tillage reduces engine load and fuel consumption in zones where shallow working depth suffices, with savings proportional to depth reduction and soil resistance characteristics. Precision targeting of intensive tillage to limited areas requiring intervention decreases total operating hours and machinery depreciation. Automated guidance and implement control reduce operator fatigue while improving tillage quality consistency.

5.3. Crop Yield Stability and Resilience

Alleviating compaction in affected zones through targeted deep tillage enhances root exploration, nutrient uptake, and water access, stabilizing yields during drought periods. Maintaining optimal soil structure across heterogeneous fields reduces yield variability, with coefficients of variation decreasing by 20-35% under DSM-guided management compared to uniform practices. Multi-year studies demonstrate cumulative yield benefits as soil physical conditions improve progressively under site-specific management regimes.

5.4. Climate-Smart Tillage Practices

Reduced tillage intensity enabled by precision management decreases soil carbon dioxide emissions and preserves organic matter stocks. Strategic tillage timing informed by soil moisture mapping reduces nitrous oxide emissions associated with anaerobic conditions and nitrogen cycling. Energy efficiency gains from optimized tillage translate directly to reduced greenhouse gas emissions per unit of crop production.

6. Challenges and Future Perspectives

6.1. Data Resolution and Uncertainty

Achieving soil property map resolutions matching variable tillage equipment capabilities requires dense sampling or sensor coverage that may exceed practical feasibility in many farming contexts. Prediction uncertainty in DSM outputs, particularly for subsurface properties and in complex terrain, necessitates cautious interpretation and risk-informed decision-making. Temporal stability of soil maps depends on property dynamics, with compaction states changing seasonally while texture remains largely constant.

6.2. Model Transferability Across Regions

Machine learning models trained in specific pedological and climatic contexts may exhibit reduced accuracy when applied to new regions with different soil-landscape relationships. Local calibration of proximal sensors and validation of remote sensing correlations remains necessary across diverse soil types and environmental conditions. Development of generalizable models and transfer learning approaches could enhance DSM applicability across broader geographic extents.

6.3. Adoption Barriers at Farm Scale

Capital investment requirements for precision tillage equipment and DSM services present financial barriers, particularly for small and medium-scale farming operations. Technical expertise needed for data interpretation, prescription development, and equipment operation may exceed available human resources on individual farms. Service provider models and cooperative arrangements offer potential pathways to broaden access to site-specific tillage technologies.

Table 2 summarizes the benefits and limitations of DSM-based tillage systems.

Table 2: Benefits and limitations of digital soil map-based site-specific tillage systems

Aspect	Benefits	Limitations
Agronomic Performance	• Targeted compaction alleviation • Optimized seedbed quality • Reduced yield variability • Enhanced soil health indicators	• Requires multi-year implementation for full benefits • Variable responses across crops and years • Need for continuous monitoring
Environmental Impact	• 30-60% erosion reduction in vulnerable zones • Soil carbon preservation • Reduced nutrient runoff • Lower GHG emissions	• Benefits depend on proper zone delineation • Potential for localized negative impacts if misapplied
Operational Efficiency	• 15-30% fuel savings • Reduced machinery wear • Labor optimization • Improved timeliness	• Equipment complexity and maintenance • Operator training requirements • Technology integration challenges
Economic Viability	• Positive ROI in 3-5 years (typical) • Input cost reduction • Yield stability premiums	• High initial capital investment • Scale-dependent economics • Variable returns across field conditions
Data & Technology	• Objective, quantitative basis for decisions • Integration with other precision tools • Continuous improvement through data accumulation	• Data acquisition costs and complexity • Model uncertainty and validation needs • Temporal data updates required

6.4 Future Integration with Autonomous Machinery

Emerging autonomous tillage systems combined with real-time sensing enable continuous adaptation of tillage parameters to instantaneous soil conditions. Sensor fusion integrating multiple proximal detection technologies promises enhanced property characterization accuracy during implement operation. Edge computing and artificial intelligence facilitate on-board decision-making for immediate tillage adjustment without reliance on pre-generated prescription maps.

Figure 4 envisions the future precision tillage system architecture.

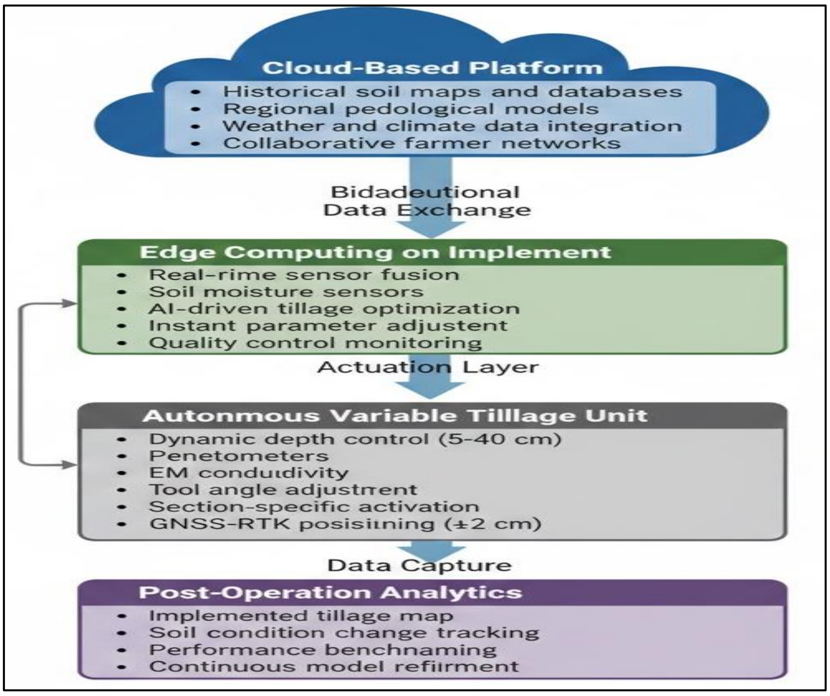

Fig 4: Future precision tillage system combining DSM, sensors, and automated machinery

7. Conclusion

Digital soil mapping has matured into a practical technology enabling the transition from uniform to site-specific tillage management across diverse agricultural systems. By quantifying and visualizing soil spatial variability at resolutions matching precision equipment capabilities, DSM provides the foundational information required to optimize tillage intensity, depth, and timing according to local soil conditions. Integration of proximal sensing, remote sensing, machine learning, and geostatistical modeling generates accurate soil property predictions that inform management zone delineation and variable rate prescription development.

Empirical evidence demonstrates substantial agronomic, environmental, and economic benefits from DSM-guided tillage, including erosion reduction, fuel savings, improved soil structure, and enhanced yield stability. These outcomes align with sustainable intensification objectives, supporting increased productivity while preserving soil resources and reducing environmental impacts. However, challenges related to data costs, model uncertainty, technology complexity, and farm-scale adoption barriers must be addressed to realize widespread implementation.

Future development priorities include: advancing autonomous tillage systems with integrated real-time sensing, improving model transferability across regions and soil types, reducing technology costs through innovation and economies of scale, and enhancing decision support tools for diverse user capabilities. The convergence of digital soil mapping with artificial intelligence, edge computing, and collaborative data platforms promises transformative advances in precision soil management.

For farmers and land managers, DSM-based site-specific tillage offers actionable strategies to enhance productivity and sustainability. For researchers and technology developers, continued innovation in sensors, models, and decision frameworks will expand the precision and accessibility of these systems. As agriculture confronts intensifying resource constraints and environmental pressures, data-driven spatial approaches to tillage management represent essential tools for building resilient and productive farming systems that safeguard soil health for future generations.

8. References

1. Paustian K, Lehmann J, Ogle S, *et al*. Climate-smart soils. Nature. 2016;532(7597):49–57.
2. Soane BD, van Ouwerkerk C. Soil compaction problems in world agriculture. Developments in Agricultural Engineering. 1994;11:1–21.
3. Brus DJ, Kempen B, Heuvelink GBM. Sampling for validation of digital soil maps. European Journal of Soil Science. 2011;62(3):394–407.
4. McBratney AB, Santos MM, Minasny B. On digital soil mapping. Geoderma. 2003;117(1–2):3–52.
5. Goovaerts P. Geostatistical approaches for incorporating elevation into the spatial interpolation of rainfall. Journal of Hydrology. 2000;228(1–2):113–129.
6. Lal R, Shukla MK. Principles of Soil Physics. New York: Marcel Dekker; 2004.
7. Montgomery DR. Soil erosion and agricultural sustainability. Proceedings of the National Academy of Sciences of the United States of America. 2007;104(33):13268–13272.
8. Hamza MA, Anderson WK. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. Soil and Tillage Research. 2005;82(2):121–145.
9. Pretty J. Agricultural sustainability: concepts, principles and evidence. Philosophical Transactions of the Royal Society B: Biological Sciences. 2008;363(1491):447–465.
10. Foley JA, Ramankutty N, Brauman KA, *et al*. Solutions for a cultivated planet. Nature. 2011;478(7369):337–342.
11. Lagacherie P, McBratney AB, Voltz M. Digital Soil Mapping: An Introductory Perspective. Amsterdam: Elsevier; 2007.
12. Minasny B, McBratney AB. Digital soil mapping: a brief

history and some lessons. Geoderma. 2016;264:301–311.

13. Adamchuk VI, Hummel JW, Morgan MT, Upadhyaya SK. On-the-go soil sensors for precision agriculture. Computers and Electronics in Agriculture. 2004;44(1):71–91.
14. Mulla DJ. Twenty five years of remote sensing in precision agriculture: key advances and remaining knowledge gaps. Biosystems Engineering. 2013;114(4):358–371.
15. Zhang N, Wang M, Wang N. Precision agriculture—a worldwide overview. Computers and Electronics in Agriculture. 2002;36(2–3):113–132.
16. Lowenberg-DeBoer J, Erickson B. Setting the record straight on precision agriculture adoption. Agronomy Journal. 2019;111(4):1552–1569.
17. Chamen WCT, Moxey AP, Towers W, *et al*. Mitigating arable soil compaction: a review and analysis of available cost and benefit data. Soil and Tillage Research. 2015;146:10–25.
18. Godwin RJ, O'Dogherty MJ. Integrated soil tillage force prediction models. Journal of Terramechanics. 2007;44(1):3–14.
19. Fountas S, Pedersen SM, Blackmore S. ICT in precision agriculture—diffusion of technology. In: ICT in Agriculture: Perspectives of Technological Innovation. 2005. p. 1–18.
20. Bramley RGV. Lessons from nearly 20 years of precision agriculture research, development, and adoption as a guide to its appropriate application. Crop and Pasture Science. 2009;60(3):197–217.
21. Dexter AR. Advances in characterization of soil structure. Soil and Tillage Research. 1988;11(3–4):199–238.
22. Watts CW, Dexter AR. Soil friability: theory, measurement and the effects of management and organic carbon content. European Journal of Soil Science. 1998;49(1):73–84.
23. Arvidsson J, Håkansson I. Response of different crops to soil compaction—short-term effects in Swedish field experiments. Soil and Tillage Research. 2014;138:56–63.
24. Lyles L, Tatarko J. Wind erosion effects on soil texture and organic matter. Journal of Soil and Water Conservation. 1986;41(3):191–193.
25. Lipiec J, Hatano R. Quantification of compaction effects on soil physical properties and crop growth. Geoderma. 2003;116(1–2):107–136.
26. Vaz CMP, Manieri JM, de Maria IC, Tuller M. Modeling and correction of soil penetration resistance for varying soil water content. Geoderma. 2011;166(1):92–101.
27. Keller T, Arvidsson J, Schjønning P, *et al*. In situ subsoil stress-strain behavior in relation to soil precompression stress. Soil Science. 2012;177(8):490–497.
28. Munkholm LJ, Heck RJ, Deen B. Long-term rotation and tillage effects on soil structure and crop yield. Soil and Tillage Research. 2013;127:85–91.
29. Głąb T, Kulig B. Effect of mulch and tillage system on soil porosity under wheat. Soil and Tillage Research. 2008;99(2):169–178.
30. Six J, Bossuyt H, Degryze S, Denef K. A history of research on the link between aggregates, soil biota, and soil organic matter dynamics. Soil and Tillage Research. 2004;79(1):7–31.
31. Blanco-Canqui H, Lal R. Soil organic matter and water retention. In: Lal R, editor. Principles of Soil Conservation and Management. Dordrecht: Springer; 2009. p. 155–177.
32. Gessler PE, Moore ID, McKenzie NJ, Ryan PJ. Soil-landscape modelling and spatial prediction of soil attributes. International Journal of Geographical Information Systems. 1995;9(4):421–432.
33. Webster R, Oliver MA. Geostatistics for Environmental Scientists. 2nd ed. Chichester: Wiley; 2007.
34. Pennock DJ, Zebarth BJ, De Jong E. Landform classification and soil distribution in hummocky terrain. Geoderma. 1987;40(3–4):297–315.
35. Gregorich EG, Greer KJ, Anderson DW, Liang BC. Carbon distribution and losses: erosion and deposition effects. Soil and Tillage Research. 1998;47(3–4):291–302.
36. Fridgen JJ, Kitchen NR, Sudduth KA, *et al*. Management zone analyst: software for subfield management zone delineation. Agronomy Journal. 2004;96(1):100–108.
37. Hornung A, Khosla R, Reich R, *et al*. Comparison of site-specific management zones. Agronomy Journal. 2006;98(2):407–415.
38. Fleming KL, Westfall DG, Wiens DW, Brodahl MC. Evaluating farmer-defined management zone maps for variable rate fertilizer application. Precision Agriculture. 2000;2(2):201–215.
39. Moral FJ, Terrón JM, Rebollo FJ. Site-specific management zones based on the Rasch model and geostatistical techniques. Computers and Electronics in Agriculture. 2011;75(2):223–230.
40. Odeh IOA, McBratney AB, Chittleborough DJ. Further results on prediction of soil properties from terrain attributes. Geoderma. 1995;67(3–4):215–226.
41. Corwin DL, Lesch SM. Apparent soil electrical conductivity measurements in agriculture. Computers and Electronics in Agriculture. 2005;46(1–3):11–43.
42. Burgos P, Madejón E, Pérez-de-Mora A, Cabrera F. Spatial variability of the chemical characteristics of a trace-element-contaminated soil before and after remediation. Geoderma. 2006;130(1–2):157–175.
43. Soil Survey Staff. Soil Survey Manual. Washington, DC: United States Department of Agriculture; 2017.
44. Grunwald S, Thompson JA, Boettinger JL. Digital soil mapping and modeling at continental scales. Geoderma. 2011;150(1–2):1–7.
45. Minasny B, McBratney AB. A conditioned Latin hypercube method for sampling in the presence of ancillary information. Computers & Geosciences. 2006;32(9):1378–1388.