Sustainable Off-Road Machinery Design: Reducing Soil Damage through Terrain–Machine Interaction Modeling

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Abstract

Off-road machinery used in forestry, agriculture, land management, construction, and field logistics must operate across deformable, sloped, wet, rooted, and otherwise sensitive terrain. While such machines are essential for industrial productivity, they can also cause soil compaction, rutting, root damage, excessive slip, high contact pressure, increased fuel consumption, and long-term reduction of terrain productivity. Sustainable off-road machinery design therefore requires more than increased engine power, larger tires, or higher load capacity. It requires a systematic understanding of terrain–machine interaction.

This article proposes an engineering framework for reducing soil damage through terrain–machine interaction modeling. The framework integrates soil bearing capacity, wheel–soil contact mechanics, root reinforcement, tire or track configuration, machine weight distribution, slip behavior, and mobility prediction into an applied design process for off-road machinery. Special attention is given to forestry machines operating on rooted soft soil and sloped terrain, where trafficability, productivity, operator safety, and environmental protection must be considered simultaneously.

The article presents a practical modeling workflow, key engineering parameters, soil damage indicators, design strategies, an illustrative evaluation matrix, and future research directions. The proposed framework supports sustainable off-road machine development by connecting terramechanics, mechanical design, simulation-based engineering, sensor-assisted monitoring, and environmentally responsible machinery optimization.

Keywords: terramechanics; off-road machinery; forestry machines; soil compaction; terrain–machine interaction; rooted soil; sustainable machinery; mobility prediction; machine design; soil bearing capacity.

1. Introduction

Off-road machinery plays an essential role in forestry, agriculture, mining, construction, emergency response, and land management. These machines are required to perform demanding tasks in environments where conventional road vehicles cannot operate. Unlike vehicles that travel on rigid paved surfaces, off-road machines interact with deformable and highly variable terrain, including soft soil, rooted forest soil, clay, sand, marshland, wet ground, sloped terrain, and rough natural surfaces.

In forestry and agricultural operations, machinery productivity must be balanced with the preservation of soil structure, vegetation, root systems, and long-term land usability. Heavy machines may increase operational speed and carrying capacity, but they may also increase rut depth, soil compaction, shear damage, root disturbance, and energy losses caused by slip and sinkage. These negative effects are particularly important in forestry operations, where repeated traffic on wet or rooted soil may affect tree growth, soil health, and the ecological function of the forest floor.

Classical terramechanics established the importance of studying the interaction between vehicles and deformable terrain as an integrated mechanical system rather than as two separate engineering problems (Bekker, 1969; Wong, 2008). This principle remains highly relevant for modern off-road machinery. A machine that performs well on hard terrain may perform poorly on soft rooted soil. A design that improves traction may also increase shear damage. A heavier machine may increase productivity but create unacceptable rutting or compaction. Therefore, sustainable off-road machinery design must treat terrain response as a core design constraint.

The purpose of this article is to present a structured engineering framework for reducing soil damage through terrain–machine interaction modeling. The proposed framework is intended for application in sustainable forestry machinery, agricultural off-road equipment, and related terrain-dependent machine systems.

2. Technical Background

2.1 Terrain–Machine Interaction as a Design Problem

Traditional machine design often focuses on power transmission, structural strength, productivity, durability, and cost. In off-road machinery, however, machine performance is also controlled by terrain response. Soil deformation can reduce traction efficiency, increase rolling resistance, produce rutting, damage root systems, and limit machine mobility.

Terrain–machine interaction includes several interconnected engineering phenomena. These include sinkage, which refers to vertical penetration of a tire, wheel, or track into the soil; slip, which describes relative motion between the traction unit and terrain; shear deformation, which involves horizontal displacement and failure of soil under traction forces; compaction, which increases soil density and reduces pore space; rutting, which creates permanent deformation of the soil surface; root damage, which may result from compression, shear, or displacement; and mobility loss, which reduces the machine's ability to continue moving efficiently.

These phenomena are interconnected. For example, high contact pressure may increase sinkage; increased sinkage may increase rolling resistance; increased rolling resistance may require higher traction force; higher traction force may increase slip and shear deformation. A sustainable design must therefore minimize damaging soil effects while maintaining adequate machine mobility, traction, stability, and productivity.

2.2 Forestry Machines as a Critical Case

Forestry machines are especially important in terrain–machine interaction research because they often operate on uneven, wet, rooted, and low-bearing-capacity soils. Forwarders, harvesters, skidders, and other forestry machines may carry heavy loads while traveling repeatedly along forest routes. These operating conditions create a high risk of soil compaction, root damage, excessive rutting, and long-term ecological disturbance.

Forest soil is not a simple homogeneous material. It may include mineral soil, organic matter, moisture, stones, roots, and vegetation layers. Root systems may increase soil shear strength and bearing capacity, but the same roots may also be damaged if machine loads produce excessive compression, shear, or displacement. Pirnazarov and Sellgren (2015) demonstrated the importance of rooted soil bearing capacity for wheeled forestry machines and showed that root reinforcement can be relevant to wheel–soil interaction modeling.

This creates a design challenge: sustainable forestry machines must maintain mobility while limiting soil and root damage. It is not enough to ask whether a machine can cross soft terrain. The design question is whether the machine can cross such terrain while maintaining acceptable soil disturbance, root protection, stability, energy efficiency, and operator safety.

2.3 Soil Compaction and Environmental Impact

Soil compaction can affect soil porosity, water movement, aeration, microbial activity, and root growth. In forest environments, heavy machinery can alter soil structure and biological function. Frey et al. (2009) showed that heavy logging machinery can affect forest soil bacterial community structure, demonstrating that machinery-induced soil disturbance may have ecological consequences beyond visible rutting.

From an engineering perspective, soil damage is not only an environmental issue. It is also a machine performance issue. Excessive rutting increases rolling resistance, reduces mobility, increases fuel consumption, and may require additional recovery or route maintenance. Therefore, reducing soil damage can support both sustainability and operational efficiency.

2.4 Need for Simulation-Based Design

Field testing remains valuable, but it is expensive, time-consuming, location-specific, and difficult to repeat under identical soil and moisture conditions. Simulation-based design allows engineers to evaluate machine concepts before full-scale prototyping and to compare alternative designs under controlled conditions.

Simulation approaches are especially useful when evaluating machine configurations such as low-pressure tires, tracks, bogies, active suspension systems, chassis designs, or adaptive traction control. Ismoilov, Sellgren, and Andersson (2017) developed a dynamic base model of a bogie-suspended forwarder, demonstrating the relevance of multi-body dynamic modeling for forestry machine design.

A modern terrain–machine interaction framework should support the prediction of contact pressure and sinkage, estimation of rut depth, analysis of slip and traction efficiency, evaluation of soil bearing capacity, assessment of load distribution among wheels or tracks, comparison of tire, track, suspension, and chassis alternatives, and integration with digital twin or sensor-based monitoring systems.

3. Objective of the Proposed Framework

The objective of this article is to propose a practical design framework for reducing soil damage through terrain–machine interaction modeling.

The framework is designed to help engineers answer the following questions:

1. How does machine configuration affect soil compaction and rutting?

2. How can wheel or track contact pressure be reduced without sacrificing mobility?
3. How can soil bearing capacity be incorporated into off-road machine design?
4. How can rooted soil models support sustainable forestry machinery development?
5. How can simulation-based design reduce the need for excessive field testing?
6. What performance indicators should be used to compare alternative off-road machine concepts?
7. How can sensor-based monitoring improve adaptive control of off-road machinery?

The framework is intended for use in early-stage concept design, simulation-based comparison, technical feasibility analysis, and sustainability-oriented machine optimization.

4. Terrain–Machine Interaction Modeling Framework

The proposed framework consists of six main stages:

1. Terrain characterization;
2. Machine configuration modeling;
3. Contact mechanics modeling;
4. Mobility and soil damage prediction;
5. Design comparison;
6. Sustainability-oriented optimization.

This structure is consistent with classical terramechanics principles, but it also incorporates modern simulation-based and sensor-assisted engineering approaches (Bekker, 1969; Wong, 2008; He et al., 2019).

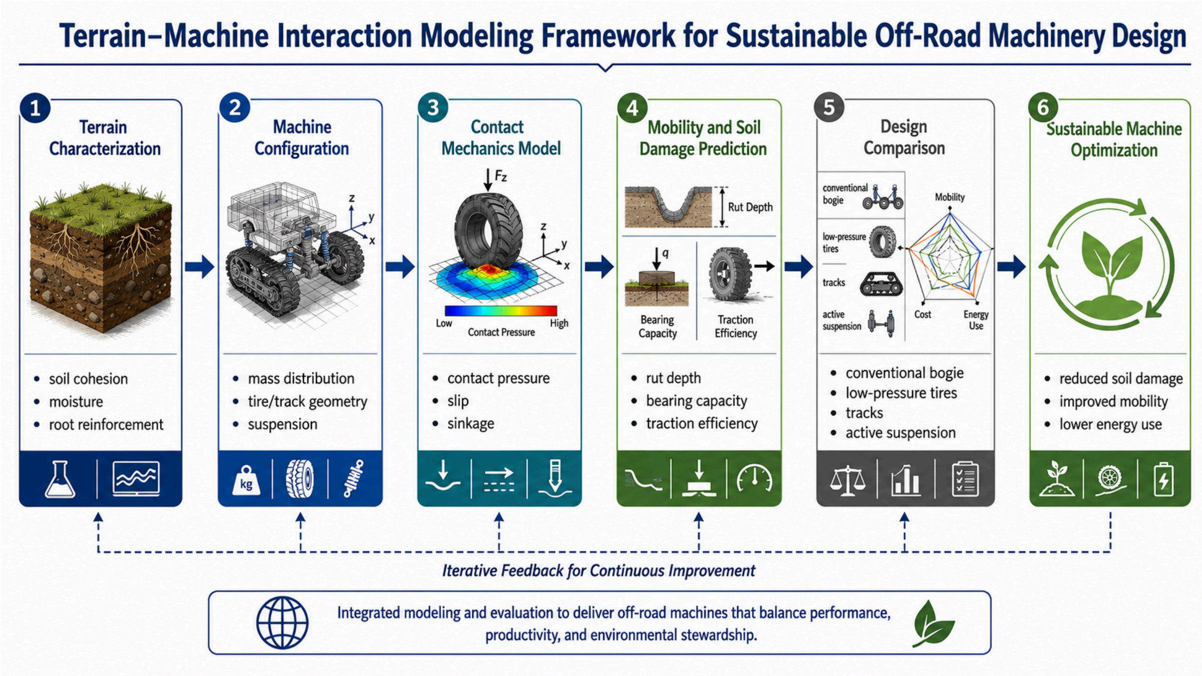

Figure 1. Terrain–Machine Interaction Modeling Framework for Sustainable Off-Road Machinery Design

5. Model Inputs and Engineering Parameters

A terrain–machine interaction model must include both machine-side and terrain-side variables. Table 1 summarizes the main input parameters relevant to sustainable off-road machine design.

Table 1. Key Parameters for Terrain–Machine Interaction Modeling

Category	Parameter	Engineering Meaning	Relevance to Soil Damage Reduction
Terrain	Soil cohesion	Resistance of soil particles to separation	Higher cohesion may improve bearing capacity
Terrain	Internal friction angle	Soil shear resistance under normal load	Affects traction and slope stability
Terrain	Soil moisture	Water content in soil	High moisture usually increases rutting risk

Terrain	Root area ratio	Root contribution to soil reinforcement	Important for forest soil bearing capacity
Terrain	Terrain slope	Ground inclination	Affects load transfer and machine stability
Machine	Total mass	Machine weight including load	Higher mass increases contact pressure
Machine	Axle load	Load distribution among wheels or tracks	Uneven distribution increases localized damage
Machine	Contact area	Tire or track contact patch	Larger contact area can reduce pressure
Machine	Tire inflation pressure	Tire stiffness and contact behavior	Lower pressure may reduce compaction
Machine	Slip ratio	Difference between wheel rotation and forward motion	High slip increases shear damage
Machine	Suspension type	Passive, semi-active, or active chassis response	Can improve load distribution and stability
Output	Contact pressure	Load applied to soil per unit area	Core indicator of compaction risk
Output	Rut depth	Permanent terrain deformation	Direct soil disturbance indicator
Output	Traction efficiency	Useful drawbar power relative to losses	Links sustainability and energy efficiency
Output	Mobility margin	Ability to continue moving without immobilization	Determines trafficability
Output	Soil damage index	Combined indicator of compaction, rutting, and shear	Useful for comparing design alternatives

The exact parameters selected for a model should depend on the intended machine type and operating environment. A model for forestry forwarders may emphasize root reinforcement, rutting, load distribution, and slope stability. A model for agricultural machinery may emphasize soil compaction, tire pressure, repeated passes, and seasonal soil moisture. A model for robotic ground vehicles may emphasize real-time terrain estimation, slip prediction, and autonomous route planning.

6. Conceptual Mathematical Structure

A simplified terrain–machine model can be organized around contact pressure, soil bearing capacity, slip, and soil damage indicators.

6.1 Contact Pressure

Average ground contact pressure can be estimated conceptually as:

$$P_c = W_i / A_i$$

In this expression, **Pc** represents average contact pressure, **Wi** represents the load carried by wheel or track unit *i*, and **Ai** represents the effective contact area of wheel or track unit *i*.

Reducing contact pressure can be achieved by lowering machine mass, improving load distribution, increasing contact area, optimizing tire inflation pressure, or using track-based systems. However, reducing contact pressure alone is not sufficient. Shear deformation and slip must also be considered because a machine can damage soil through horizontal forces even when vertical pressure is moderate.

6.2 Soil Bearing Capacity

Soil bearing capacity can be expressed as a function of cohesion, soil friction, unit weight, contact geometry, and root reinforcement. For rooted forest soil, root reinforcement may be treated as an additional contribution to apparent cohesion when roots remain undamaged (Pirnazarov & Sellgren, 2015).

A simplified conceptual relationship can be written as:

$$\mathbf{Q_r = f(c, \varphi, \gamma, b, z, \Delta S_r)}$$

In this relationship, **Qr** represents rooted soil bearing capacity, **c** represents soil cohesion, **φ** represents the internal friction angle, **γ** represents soil unit weight, **b** represents the width of the contact surface, **z** represents deformation depth or rut depth, and **ΔSr** represents the root reinforcement contribution.

A sustainable machine should operate with contact pressure and shear stress below critical thresholds that would produce excessive rutting, compaction, or root damage.

6.3 Slip and Shear Damage

Slip ratio is a key indicator of traction inefficiency and soil shear disturbance. Excessive slip can damage soil even when vertical contact pressure is moderate.

A simplified traction condition can be expressed as:

$$T \leq S_{soil}$$

In this expression, **T** represents the required traction force, while **Ssoil** represents the available soil shear resistance.

When required traction exceeds soil shear resistance, slip, rutting, and loss of mobility become more likely. This is why traction control, route planning, and machine weight distribution are important sustainability tools in off-road machine design.

7. Proposed Soil Damage Index

To compare machine alternatives, a combined soil damage index may be used. This index should not replace field measurements, but it can support early-stage design evaluation and simulation-based comparison.

A conceptual soil damage index may include four normalized components:

$$SDI = w_1R + w_2C + w_3S + w_4D$$

In this expression, **SDI** represents the soil damage index, **R** represents normalized rut depth, **C** represents normalized compaction risk, **S** represents normalized slip-related shear disturbance, **D** represents normalized root damage risk, and **w1, w2, w3, and w4** represent weighting factors selected according to operational priorities.

For forestry applications, root damage and rutting may receive higher weighting. For agricultural operations, compaction and repeated traffic may be more important. For autonomous off-road vehicles, mobility margin and slip control may receive additional emphasis. A soil damage index should be calibrated with field measurements when used for operational decision-making.

8. Design Strategies for Reducing Soil Damage

Table 2 summarizes engineering strategies that can reduce soil damage in off-road machinery.

Table 2. Design Strategies for Sustainable Off-Road Machinery

Design Strategy	Expected Benefit	Potential Limitation	Best Application
Wider tires	Lower average contact pressure	May increase machine width	Forestry and agricultural transport
Low-pressure tires	Larger contact area and reduced compaction	May reduce durability or increase rolling resistance	Wet or soft terrain
Tracks	Reduced ground pressure and improved flotation	May increase shear during turning	Soft soil and low-bearing terrain
Load distribution control	Reduced localized wheel overload	Requires sensors or active systems	Sloped or uneven terrain
Active or semi-active suspension	Improved stability and load sharing	Higher system complexity	Rough terrain and operator comfort
Route planning	Avoids weak soils and repeated passes	Requires terrain data	Precision forestry and agriculture
Slip control	Reduces shear damage and energy losses	Requires control algorithms	Automated and semi-autonomous machines
Modular machine mass	Adjusts machine weight to terrain sensitivity	Operational complexity	Variable terrain operations
Digital terrain mapping	Supports trafficability prediction	Requires data collection	Large-area operations

Predictive maintenance	Maintains traction and suspension performance	Requires monitoring system	High-utilization machinery

These strategies should not be considered separately. For example, low-pressure tires may reduce contact pressure but may not prevent shear damage if slip remains high. Active suspension may improve load distribution, but it may require sensor integration and control logic. Route planning may reduce soil disturbance, but only if terrain data are reliable.

9. Conceptual Comparison of Machine Alternatives

For early-stage design, machine concepts may be compared using normalized scores. Table 3 presents an illustrative evaluation matrix. The values are conceptual and should be replaced with simulation or field-test data in a final engineering study.

Table 3. Illustrative Design Evaluation Matrix for Off-Road Forestry Machines

Machine Concept	Contact Pressure Score	Mobility Score	Rutting Reduction Score	Operator Stability Score	Energy Efficiency Score	Overall Sustainability Score
Conventional wheeled forwarder	45	60	40	45	55	49
Low-pressure tire configuration	65	62	60	50	58	59
Tracked machine configuration	78	72	70	55	50	65
Active suspension forwarder	70	75	68	82	60	71

Sensor-assisted adaptive traction system	75	80	73	78	72	76

Note: *The values in Table 3 are illustrative and are intended to demonstrate a design evaluation structure. They are not presented as field-measured results.*

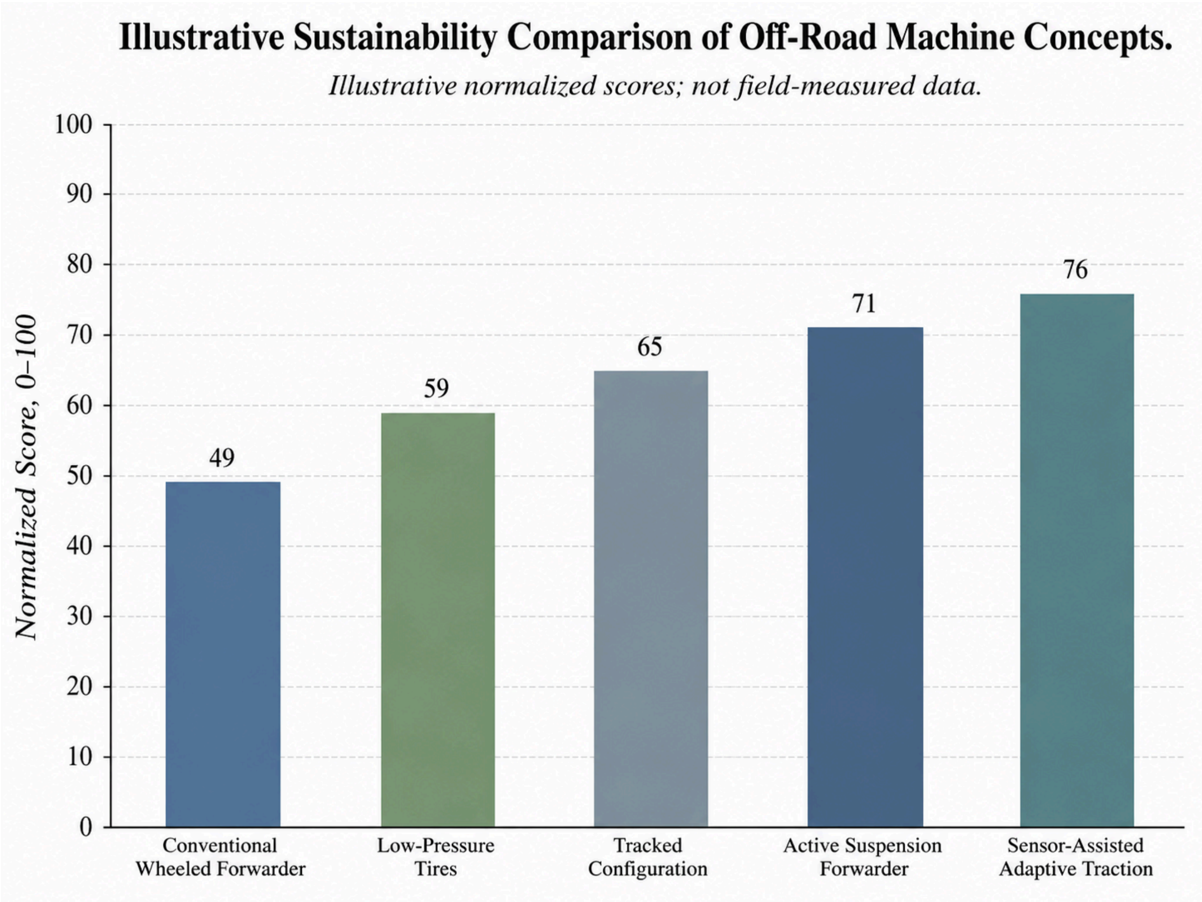

Figure 2. Comparative Sustainability Scores of Off-Road Machine Concepts

10. Design Framework for Sustainable Machine Development

The proposed design framework is based on the principle that sustainability should be incorporated at the beginning of machine development rather than added after the machine is already designed.

10.1 Define Terrain Sensitivity

The first step is to classify the expected terrain. Relevant terrain categories may include hard mineral soil, wet soft soil, rooted forest soil, marshland, clay, sand, sloped terrain, and mixed terrain.

Each terrain class should be assigned sensitivity factors for compaction, rutting, slip, and root damage. Soil interaction models developed in forestry and agricultural contexts can support this process, especially when combined with field observations and terrain classification (Saarilahti, 2002).

10.2 Define Machine Operating Conditions

The next step is to define the machine operating conditions, including total machine mass, loaded and unloaded operating modes, tire or track configuration, travel speed, expected number of passes, slope angle, route length, operational season, and load distribution.

A machine may have acceptable soil impact when unloaded but unacceptable soil impact when fully loaded. Therefore, sustainable design must evaluate multiple load cases.

10.3 Build a Contact Model

A contact model should estimate contact area, ground pressure, wheel or track load, vertical sinkage, slip ratio, shear stress, and rolling resistance.

The model should represent both vertical and horizontal machine–soil interaction. Contact pressure alone is not sufficient because shear deformation and slip can produce significant terrain damage.

10.4 Add Rooted Soil or Terrain Reinforcement Model

For forestry operations, rooted soil should not be treated as ordinary homogeneous soil. Root reinforcement may increase bearing capacity, but roots must also be protected from breakage and excessive displacement. Pirnazarov and Sellgren (2015) showed that rooted soil properties can be used to model bearing capacity for wheel–soil interaction studies.

A sustainable model should evaluate whether operating loads remain below thresholds that may cause root system damage.

10.5 Simulate Alternative Machine Configurations

Alternative designs may include conventional wheeled systems, low-pressure tire configurations, tracked systems, bogie systems, active suspension, hybrid wheeled-track designs, sensor-assisted traction control, and adaptive route planning systems.

Multi-body simulation can be useful for evaluating dynamic behavior, load distribution, vibration, and chassis response in off-road forestry machines (Ismoilov et al., 2017).

10.6 Optimize for Multi-Objective Performance

The final design should balance low soil damage, adequate mobility, high productivity, operator safety, low fuel or energy use, mechanical reliability, maintainability, and cost.

A design that minimizes rutting but greatly reduces productivity may not be practical. A design that maximizes productivity but causes severe soil damage is not sustainable. The purpose of the framework is to support balanced engineering decisions.

11. Integration with Sensors and Digital Control

Modern sustainable off-road machinery can benefit from sensor-based monitoring and adaptive control. Sensors can measure or estimate wheel slip, tire pressure, wheel load, vibration, chassis angle, terrain slope, soil moisture, rut depth, traction efficiency, and fuel or energy consumption.

These data can support adaptive systems that adjust tire pressure, traction control, machine speed, route selection, or suspension behavior. Real-time terrain estimation and deformable-terrain modeling have become increasingly important for autonomous and semi-autonomous ground vehicles (Dallas et al., 2019). Machine learning methods may also support terrain classification and slip estimation in ground robots (González & Iagnemma, 2018).

He et al. (2019) reviewed terramechanics models and their applicability to real-time applications, showing the importance of balancing model accuracy with computational efficiency. This is highly relevant for future off-road machines that may use embedded sensors and control systems to reduce soil damage while maintaining mobility.

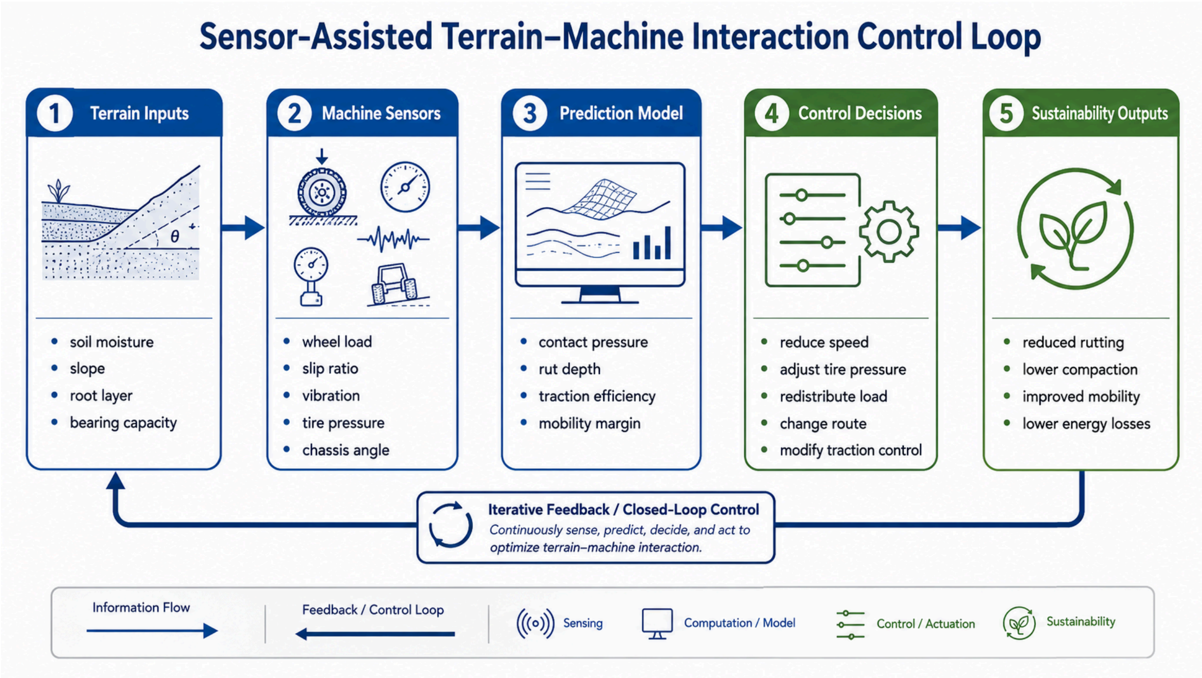

Figure 3. Sensor-Assisted Terrain–Machine Interaction Control Loop

12. Relevance to U.S. Industrial and Environmental Priorities

Sustainable off-road machinery design is relevant to multiple U.S. sectors, including forestry, agriculture, construction, land restoration, emergency logistics, and autonomous ground vehicles. In these sectors, machines must be productive but also environmentally responsible, energy-efficient, and capable of operating under complex terrain conditions.

The proposed framework supports U.S.-relevant engineering objectives by:

1. reducing soil compaction and rutting;
2. improving machine trafficability;
3. extending equipment usability in variable terrain;
4. supporting automation and sensor-based machinery control;
5. improving sustainability of forestry and agricultural operations;
6. reducing unnecessary field testing through simulation-based design;

7. supporting development of advanced mechanical systems for difficult terrain.

The framework is therefore relevant not only to forestry machinery but also to broader industrial machinery innovation, including robotic ground vehicles, agricultural machinery, and automated off-road platforms.

13. Practical Application Scenario

A practical application of the proposed framework may involve the development of a new off-road forestry machine intended to operate on soft rooted soil in wet seasons.

The design process may proceed as follows:

1. Collect soil data, including cohesion, moisture content, root layer depth, and bearing capacity.
2. Define machine load cases for empty, half-loaded, and fully loaded operation.
3. Build a multi-body machine model with tire or track contact modules.
4. Estimate contact pressure, slip, rut depth, and traction efficiency.
5. Compare alternative tire sizes, tire pressures, bogie layouts, and suspension systems.
6. Select the design that minimizes soil damage while maintaining acceptable mobility and productivity.
7. Validate the model through controlled field testing.
8. Integrate sensors for real-time monitoring and adaptive machine control.

This process can reduce design uncertainty and support more sustainable machine development.

14. Limitations

The proposed framework is intended as a structured engineering approach rather than a substitute for field validation. Terrain is highly variable, and soil response depends on moisture, vegetation, season, repeated traffic, organic matter, slope, and local geological conditions.

Several limitations must be considered:

1. Soil parameters may vary significantly within a single operating area.
2. Root reinforcement is difficult to measure and may change by species, depth, age, and season.
3. Simplified terramechanics models may not capture all dynamic effects.
4. Contact pressure alone is not sufficient to predict damage; slip and shear must also be included.
5. Sensor-based systems require calibration and reliability testing.
6. Simulation models should be validated with field measurements before operational deployment.
7. A single soil damage index cannot fully represent all ecological, mechanical, and operational consequences of off-road machine traffic.

These limitations do not reduce the value of modeling. Instead, they show why a transparent and carefully validated modeling framework is necessary.

15. Future Research Directions

Future research may focus on:

1. developing reduced-order models for real-time prediction of rutting and slip;
2. integrating soil moisture sensors with mobility prediction algorithms;
3. creating digital twins for forestry and agricultural machinery;
4. comparing wheeled, tracked, and hybrid traction systems under identical terrain conditions;
5. developing root-sensitive trafficability models for sustainable forestry;
6. applying machine learning to predict soil damage based on machine and terrain data;
7. designing adaptive suspension and traction systems for reduced terrain disturbance;
8. evaluating autonomous route planning for soil protection;
9. combining field data, multi-body simulation, and machine learning for operational decision support;

10. developing engineering standards for sustainable operation of heavy off-road machinery on sensitive terrain.

Reports on soil compaction and forest exploitation emphasize the importance of avoiding excessive soil deformation and developing practical guidance for machinery operation on sensitive soils (Kremers & Boosten, 2018). Soil quality assessment approaches can also help connect mechanical soil disturbance to broader indicators of soil health (Amacher et al., 2007).

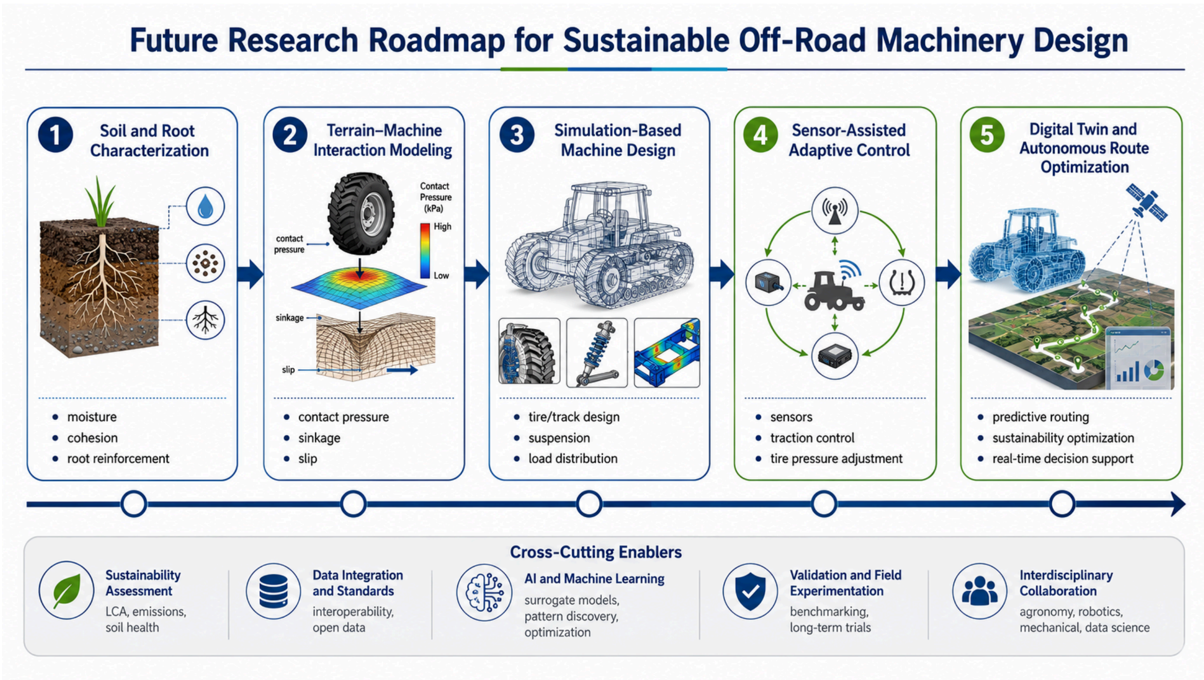

Figure 4. Future Research Roadmap for Sustainable Off-Road Machinery Design

16. Conclusion

Sustainable off-road machinery design requires an integrated understanding of terrain response, machine configuration, contact mechanics, mobility, and soil protection. Heavy off-road machines cannot be optimized only for productivity; they must also be evaluated for their effects on soil structure, root systems, rutting, compaction, and long-term terrain usability.

This article proposed a terrain–machine interaction modeling framework for reducing soil damage in off-road machinery design. The framework integrates terrain characterization, contact mechanics, root reinforcement, mobility prediction, design comparison, and sustainability-oriented optimization.

The proposed approach is especially relevant to forestry machines operating on rooted soft soil and sloped terrain, but it may also be applied to agricultural machinery, robotic ground vehicles, and other off-road industrial systems. By combining terramechanics, simulation-based design, sensor-assisted control, and sustainable engineering principles, future off-road machinery can be designed to achieve both high performance and reduced environmental impact.

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