

**Designing a Robot to Measure Soil Hydrophobicity and Optimize Tilling for Hydration**

**Grant Proposal**

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### **Executive Summary**

Wildfires have become a dominant driver of forest loss, causing almost half of all tree loss per year between 2023 and 2024. This is a sharp increase from 2001-2022, when fires accounted for a quarter of annual tree coverage loss (MacCarthy et al., 2025). Forest recovery is only worsened when some areas of soil become hydrophobic, reducing water infiltration and creating conditions that hinder vegetation regrowth. Targeted interventions to remediate hydrophobic soils are critical for supporting reforestation and accelerating regrowth. Although methods such as the water droplet penetration time (WDPT) test are used to identify hydrophobic soils, conducting these processes is labor-intensive and prone to human error. This project researched the viability of an automated robot for detecting and selectively treating hydrophobic soil. The proposed approach addresses limitations of existing methods and holds potential for improving post-wildfire soil restoration while minimizing soil disturbance.

*Keywords:* soil hydrophobicity, soil scarification, water droplet penetration time, tillage, wildfires

## Designing a Robot to Measure Soil Hydrophobicity and Optimize Tilling for Hydration

As global climates become warmer and drier, wildfires are becoming increasingly frequent. Since the 1980s, there has been a tenfold increase in fire activity, burning millions of hectares of land worldwide. The number of large wildfires has increased in the United States at a frightening pace and is predicted to continue rising due to the changing climate and human activities (Farid et al., 2024). These events have substantial hydrogeological impacts, including effects on soil health and stability.

### Wildfire's Effect on Soil:

During high-severity wildfires, organic compounds such as waxes, lipids, and resins in vegetation are vaporized. These gases condense in the cooler soil layers as they move downwards, creating a hydrophobic coating that prevents water penetration. Soil hydrophobicity refers to the ability of soil to repel water. A hydrophobic layer of soil prompts many issues, such as sediment in waterways, increased risk of debris flows and flash floods, higher erosion risks, and nutrient loss. The strength and depth of the hydrophobic layer can depend on the intensity and temperature of the wildfire, with water repellency increasing significantly between 175°C and 270°C. It can be seen in various textures of soil and often restores itself gradually over time (Li et al., 2021). However, water-repelling soil still hinders seed germination, plant growth, and overall ecosystem health, making its quick restoration critical. Furthermore, if the hydrophobic layer is not broken, conventional vegetation efforts will be unsuccessful. It will be difficult for plants to access moisture, and seeds will be less likely to germinate.

### Detecting Hydrophobic Soil:

One common method of detecting hydrophobic soil is the water droplet penetration time (WDPT) test. This test examines the time it takes for a water droplet to infiltrate the soil completely and is often used in the field to determine soil hydrophobicity. A material is considered water repellent if the time calculated is greater than 5



Figure 1. The water drop penetration time (WDPT) test performed on soil 1 cm below the surface (Robichaud et al., 2008).

seconds. As time increases, the soil is classified as more hydrophobic (Ma et al., 2025). For instance, a WDPT time greater than one minute indicates strongly water repellent soil. The WDPT test is commonly preferred over other techniques because it is inexpensive and easy to perform in the field (Dekker et al., 2009).

**Treatment of Hydrophobic Soil:**

After identifying hydrophobic areas, it is essential to treat the soil to prevent further degradation and to speed up the soil recovery process. Soil scarification through methods such as tillage has been observed to improve water infiltration (Figure 2). Tilling mechanically breaks up the water-repellent layer of the soil and can increase its porosity, improving water penetration. Studies show

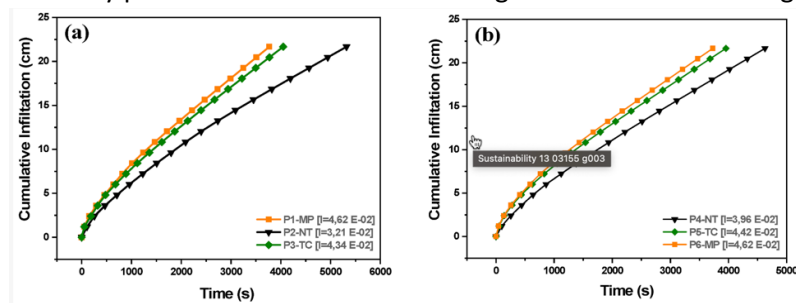


Figure 2. Cumulative infiltration over time for: (a) subplots P1, P2 and P3; (b) subplots P4, P5 and P6. MP (Moldboard Plow) and TC (Tine Cultivator) are forms of tillage. NT stands for no-tillage (Amami et al., 2021).

that seeding combined with soil scarification has more seed growth than seeding without scarification (Rhoades et al., 2015). However, tillage has its risks. When applied to soil that is not hydrophobic, it can increase erosion risks by loosening the soil, making it vulnerable to factors such as wind. This makes distinguishing between hydrophobic and non-hydrophobic soil critical before treatment. Furthermore, the depth of the tillage should be carefully considered. While a lack of tillage can increase the chances of soil hydrophobicity, deep tillage can reduce organic matter in the soil (Šimon et al., 2009). As a result, performing tillage at the appropriate depth is the most effective method of hydrophobic soil recovery.

**Robotic Systems:**

Robotic systems can reduce human discrepancies by automating labor-intensive and timeconsuming tasks such as WDPT testing in the field. The Dropbot, a drone that conducts real-time hydrophobicity testing on uneven terrain, is one notable device addressing post-wildfire soil. It uses light

sensors and camera-captured droplets with AI analysis to perform WDPT testing. Its on-site data processing allows it to generate results without needing laboratory testing. Through these components, the Dropbot provides a field-ready system for soil characterization (Prakash, 2025). However, its primary focus is on data testing and acquisition rather than soil recovery and improvement. Another project for soil rehabilitation is the ReGenBot, a robot designed for soil analysis and treatment distribution.

ReGenBot is a ground robot powered by solar energy that is equipped with tank treads for mobility and ultrasonic sensors for obstacle detection. It is able to collect data on nutrient content, temperature, and soil moisture and then distribute fertilizers and treatment based on user specifications. By measuring soil properties and delivering treatment, ReGenBot helps improve soil recovery. Still, this system mainly focuses on soil nutrients rather than hydrophobicity detection or physical soil restoration. Additionally, it depends on user interpretation of data and lacks autonomous decision-making (Vinokurova et al., 2022). Essentially, there are robotic systems that can conduct soil sampling, and some are able to detect soil hydrophobicity. However, no system specifically detects soil hydrophobicity and provides mitigating strategies through tillage to prevent further soil degradation. This suggests the need for a robotic system that can detect soil hydrophobicity and autonomously conduct targeted shallow tillage to restore water-repelling soils in post-wildfire environments.

## **Section II: Specific Aims**

This proposal's objective is to design a robot that can traverse terrain, test soil for hydrophobicity, and classify the soil based on its soil water repellency level through AI analysis. The robot should autonomously use this information to determine whether the soil needs tilling and conduct shallow tillage. The work proposed here will improve soil restoration methodologies after wildfires and increase the accuracy of hydrophobic soil detection by automating the mechanism. By selectively identifying and treating hydrophobic areas, this project will mitigate risks of large-scale tillage while

improving soil structure. In the long term, the robot will accelerate overall forest regrowth by supporting vegetation recovery without disturbing intact soil.

**Specific Aim 1:** Establish a proof-of-concept hydrophobicity detection framework.

**Specific Aim 2:** Develop a model with computer vision and machine-learning for soil hydrophobicity identification and classification.

**Specific Aim 3:** Prototype a robotic shallow-tillage mechanism and workflow for targeted soil restoration.

The expected outcome of this work is the creation of an effective autonomous robot for soil hydrophobicity detection, classification, and treatment in post-wildfire soils.

### **Section III: Project Goals and Methodology**

#### **Relevance/Significance**

With wildfires becoming increasingly frequent, hydrophobic patches of soil are becoming more common issues. However, current methods for assessing hydrophobic soils are laborious and inconsistent. Addressing this gap can reduce environmental impacts and quicken reparation of wildfire-affected landscapes.

#### **Innovation**

While previous systems have measured soil water repellency or applied treatments such as fertilizers, no existing robot platform combines identification and improvement specifically for water-repelling soils. By leveraging WDPT measurements and AI-based analysis to classify soil water repellency, the robot can automatically determine which areas require tillage without disturbing healthier soil.

#### **Methodology**

The proposed project will develop a robotic system capable of identifying water-repellent soils and performing treatment. As a proof-of-concept, soil hydrophobicity will first be simulated with varying degrees of water repellency, and the water drop penetration time test will be used to measure infiltration times. This test will be conducted using a water dropper system created with a peristaltic pump and Arduino to deliver consistent droplet size and release timing. These preliminary measurements will give insight into the relationship between soil water repellency and the WDPT test as well as confirm the effectiveness of the water dropper.

The robot will measure WDPT in real-time using computer vision to track droplet absorption over time. A camera will capture a continuous video of each droplet from the moment it contacts the soil until the droplet is fully absorbed, generating a video containing information for measuring WDPT. Each video will be fed into code utilizing computer vision that will use pixel differencing to detect water droplet landing and droplet absorption, thereby measuring the water infiltration time. For cases where absorption does not occur within the video time, a convolutional neural network (CNN) will be used to classify the last frame of the video as “not absorbed.” Through the WDPT measurements from OpenCV and the CNN’s classification, the program can categorize a soil’s level of hydrophobicity from mild to severe.

Based on the model’s classification, the robot will autonomously execute shallow tillage using a CAD-designed mechanism. The tillage tool will be modeled and prototyped with adjustable depth settings so that the robot can respond proportionally to the WDPT-based severity. To evaluate the impact of tilling on hydrophobic soils, testing will be used to confirm the tool’s ability to break the water-repellent layer and improve filtration.

***Specific Aim #1:***

The objective of this aim is to create and validate a framework for measuring soil water repellency using the water drop penetration time (WDPT) test. This includes generating predictable and controllable levels of hydrophobicity using wax-treated sand, demonstrating the relationship between water repellency and WDPT, and confirming that the Arduino-controlled water-dropper system delivers droplets consistently enough for future robotic integration. To do this, hydrophobicity will be simulated using 4 wax concentrations applied to baked sand and WDPT will be manually recorded after the water dropper dispenses droplets.

**Justification and Feasibility.** Previous research has shown that wax can be applied to create hydrophobic soil surfaces. One study used paraffin wax on watershed plots and had a 90% precipitation runoff (Fink et al., 1973). This demonstrates the effectiveness of wax in simulating hydrophobic areas. Sand-based WDPT experiments have been used often due to their uniform texture, which is why my experiment also utilizes sand (Leelamanie et al., 2008).

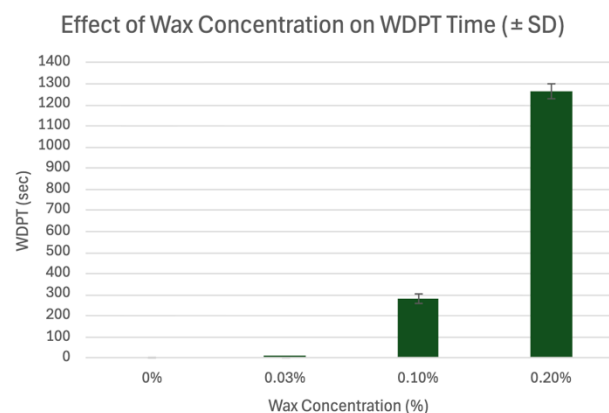
**Summary of Preliminary Data.** The preliminary data shows a clear trend: WDPT

*Figure 3. Water drop penetration time (WDPT) measurements for baked sand samples treated with wax concentrations (0%, 0.03%, 0.1%, 0.2%). Each point represents the mean WDPT from five replicate trials, with error bars indicating one standard deviation.*

increased as the wax concentration increased, confirming that the treated sand simulates hydrophobic behavior and that WDPT testing is a reliable method of measuring soil hydrophobicity. The WDPT values found have small error bars or standard deviations, demonstrating relatively low variability in the test.

This result also proves that the water dropper is functioning correctly and dispensing droplets of the same volume.

**Expected Outcomes.** The expected outcome of this aim is the establishment of a controlled and repeatable WDPT system that



can distinguish varying degrees of hydrophobicity. The water-dropper system is expected to demonstrate reliability sufficient for integration into the robotic platform. Outcomes from this aim will aid in the creation of the dataset for the machine learning model that will later be made, which will incorporate computer vision and machine learning for automated hydrophobicity detection.

**Potential Pitfalls and Alternative Strategies.** One problem that may arise is variability in droplet size, which would influence WDPT readings. As an alternative, a 3D-printed droplet guide could be made, or the pump's speed could be reduced. Wax may also be an unreliable producer of hydrophobicity. To respond, a different source of hydrophobicity could be used, such as oil or water repellent sprays.

***Specific Aim #2:***

Another goal of this project is to create a model that, using a video of water droplet absorption, is able to produce a classification for the soil's degree of hydrophobicity. By utilizing OpenCV and machine-learning, the model will be able to detect start and end times for WDPT as well as detect if absorption never occurs during the timeframe. The rationale for this approach is their ability to handle video-based input and conduct analysis that will automate the robot's decision-making.

**Justification and Feasibility.** Previous models that have been used in WDPT research, including ActionFormer and YOLOv8, utilize CNNs within their architectures (Wang et al., 2024). This demonstrates the effectiveness of convolutional neural networks with the data that will be used. Additionally, with slow movement occurring in each video, a system using pixel-differencing to find water droplet landing and absorption would be efficient, and it is known that OpenCV has those capabilities.

**Summary of Preliminary Data.** The model was tested on five video samples, and the results of its predictions are shown in Table 1. In videos 1 and 2, both methods indicated no absorption, highlighting the model’s ability to correctly identify videos in which absorption does not occur. For videos 3-5, percent error ranged from 2.6% to 23.6%, with an average percent error of approximately 11%. Considering the small sample size, the model showed a relatively good accuracy rate. It is also clear that the model seems to be consistently predicting WDPT values slightly lower than the manual measurements.

*Table 1. WDPT Measurements from Model*

Video	Model WDPT (sec)	Manual WDPT (sec)
1	No Absorption	No Absorption
2	No Absorption	No Absorption
3	17.73	23.2
4	8.83	9.4
5	2.63	2.7

*Comparison of manually measured and model-predicted WDPT videos across five video samples.*

**Expected Outcomes.** The overall outcome of this aim to produce a computer model capable of predicting relatively precise WDPT values for soil hydrophobicity detection. After detecting the WDPT values, the model will provide information to the robot on whether tillage is necessary.

**Potential Pitfalls and Alternative Strategies.** The model will inevitably have some margin of error and could have false positives or negatives while checking if absorption does not occur in the video. This is a flaw that will be seen in any model, but to increase the CNNs accuracy, it could be trained on more videos.

**Specific Aim #3:**

Another aim of this project was to develop the robot system in which the tillage mechanism and the control code are integrated. The approach is to use the Raspberry Pi with the OpenCV and ML code to control the camera, the robot motors, the tillage system, and the pump, which will be commanded through the Arduino. With the robot functional, it will be possible to achieve an automated system that measures soil hydrophobicity and dynamically adapts its treatment response.

**Justification and Feasibility.** The methods in this section are relevant because it is important to create the mechanical aspect of the system to demonstrate the model's ability to classify soil hydrophobicity and direct tillage. This robot can be made using CAD and 3D-printers as it is a prototype that will not have a heavy load.

**Expected Outcomes.** The expected outcome is for the robot to move across soil, place a droplet of water on the soil, and through the video taken by the camera, determine a tillage depth that is proportionate to soil hydrophobicity.

**Potential Pitfalls and Alternative Strategies.** As the robot is made of plastic, it may be unstable and weak. Additionally, the tillage mechanism may not be smooth because of the material. In further prototypes, metal components could be included.

### **Section III: Resources/Equipment**

For my project I will be using an Arduino Uno R3, a macOS Apple M2 computer, an Arduino to USB cable, a USB to USB-C cable, electrical tape, scissors, jumper wires, AA batteries, a micro peristaltic pump, silicone tubing (1mm ID, 2mm OD), a N-channel MOSFET, a plastic cup, a rectifier diode, a scale, beeswax, a tray, parchment paper, foil, motors, PLA, motor drivers, buck convertors, 12V battery, Raspberry Pi 5, M3 screws, wheels, and a high-resolution camera.

### **Section V: Ethical Considerations**

I will dispose of batteries, wires, and soil samples that were altered to minimize environmental harm.

### **Section VI: Timeline**

November: Finish water dropper system, obtain preliminary data

December: Use a camera to prepare WDPT videos for the CNN, begin training the CNN and making OpenCV code

January: Test and validate model, begin CAD process for robot chassis and tillage mechanism, and test robot

### Section VIII: References

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