CHAPTER 1
INTRODUCTION

1.1. Background

Soil plays a vital role as the foundation for plant growth, a natural water filter, and a provider of essential human needs, including food and fiber. As a medium for plant development, soil is not homogeneous; it comprises several layers, each with unique characteristics [1][2]. In this study, the topsoil layer is the primary focus due to its crucial role in supporting the soil ecosystem and enhancing nutrient absorption by plants. The thickness of topsoil is a key determinant of soil quality, as it provides the essential material base for plant growth [3][4]. However, topsoil is the most vulnerable soil layer to erosion, whether caused by human activities or natural factors such as rainfall and wind, significantly affecting its thickness [5]. The ideal topsoil thickness for plant growth varies depending on the plant species, climate, and soil conditions. In general, optimal topsoil thickness for plantation ranges between 15 and 30 cm [6][7]. This range provides sufficient space for root development, as well as storage for water and nutrients necessary for plant growth. In contrast, excessively thin topsoil (<15 cm) cannot retain adequate water and nutrients, which can lead to stunted growth and low crop yields [8].

Over the past few decades, pressure on soil ecosystems has increased due to human activities such as deforestation, land conversion for intensive agriculture, and urbanization. These practices have led to soil structure degradation and the loss of topsoil, ultimately reducing the land's capacity to support life. Additionally, global climate change has worsened this condition by increasing the frequency and intensity of extreme rainfall, which accelerates soil erosion in many regions [5]. These circumstances highlight the urgent need for more in-depth research to understand the factors influencing topsoil thickness and how to mitigate their adverse effects. Research on topsoil is not only important for agriculture but also for natural ecosystems and overall environmental quality. Healthy topsoil has a high capacity to sequester carbon, thereby contributing to climate change mitigation. Conversely, degraded topsoil tends to release carbon into the atmosphere, exacerbating greenhouse gas effects. Therefore, topsoil conservation has become a global priority in efforts to protect the environment and ensure the sustainability of land resources.

The soil profile excavation method is the most used approach for measuring topsoil thickness due to its high accuracy. However, this method is inefficient for collecting data over large areas. Alternative techniques such as electrical resistivity imaging (ERI) and soil probes [9], random forest modeling [10], digital elevation model (DEM) analysis [11], and landscape evolution models (LEM) or sediment profile functions (SPF) [12] have been developed to address this issue. Nevertheless, these methods have limitations related to destructiveness, implementation complexity, time consumption, and limited spatial coverage. Recent studies using radar technologies [13][14] have showed promising results in mapping soil thickness under various conditions. However, the soil structures under investigation and the radar parameters employed often vary. For instance, higher frequency radar is typically used in forest soils with organic horizons, while electrical resistivity tomography (ERT) is more suitable for karst landscapes with complex rock formations. Therefore, the development of subsurface radar technologies, such as Synthetic Frequency Continuous Wave (SFCW) radar, holds significant potential for enabling rapid, wide-area, and non-destructive estimation of topsoil thickness. Topsoil thickness is a primary indicator of soil health, which plays a vital role in ensuring the sustainability of agricultural ecosystems and the responsible management of natural resources. Numerous studies have explored the relationship between topsoil thickness and crop productivity. For example, research in the United States reported that erosion-induced loss of topsoil can reduce corn yields by up to 39% compared to areas with thicker topsoil layers [15]. In agricultural systems, uneven topsoil distribution often results in inconsistent water and nutrient availability, which can negatively impact plant growth. Additionally, studies conducted in karst landscapes have revealed that shallow soils and the complex distribution of bedrock significantly influence the soil's water retention capacity [9].

In the context of Indonesia, research on topsoil thickness remains limited, despite the high rainfall and intensive land management practices that increase the risk of soil erosion. In tropical regions, factors such as deforestation, agricultural intensification, and land-use change accelerate topsoil loss, which ultimately leads to reduced land productivity and ecosystem degradation. Therefore, a better understanding of the distribution and dynamics of topsoil thickness in this region is of critical importance. This study aims to estimate topsoil thickness using Synthetic Frequency Continuous Wave (SFCW) radar technology to explore the relationship between soil thickness, moisture content, and soil productivity potential. The outcomes of this research are expected to support sustainable land management and inform soil conservation policy in Indonesia. Furthermore, this study has the potential to provide valuable insights for developing climate change mitigation strategies through improved soil conservation and water management practices in tropical environments.

1.2. Problem Formulation

Based on the background, the research problem in this study can be formulated as follows:

1. The estimation of topsoil thickness can be achieved by analyzing the time difference between the reflection from the ground surface and the reflection from the boundary separating the topsoil and subsoil layers. This time difference provides an indirect measure of topsoil depth. To ensure accurate estimation, it

is essential to employ a method that can reliably identify the topsoil-subsoil interface. The precision in detecting this boundary plays a crucial role, especially in systems based on electromagnetic wave propagation such as Ground Penetrating Radar (GPR).

2. The electrical characteristics of soil influence the radar reflection signal. The detection of topsoil thickness fundamentally relies on the propagation of electromagnetic waves through layered media. Given that soil electrical properties can vary significantly across different areas, understanding these properties is essential to ensure the accuracy of thickness estimation. The impact of soil's electrical characteristics reflected signals particularly in the time-domain response of SFCW requires further investigation to establish a fundamental reference for method development. An effective method for estimating topsoil thickness must incorporate techniques for evaluating the soil's electrical properties. Therefore, developing and refining methods for extracting these electrical characteristics becomes a central focus in achieving accurate topsoil thickness estimation.

1.3. Research Objectives

This research aims to develop a method for estimating topsoil thickness using a Stepped Frequency Continuous Wave (SFCW) radar system, which can estimate the dielectric properties of soil. The method leverages the characteristics of electromagnetic wave propagation to enable rapid and non-invasive estimation of soil thickness. By integrating a technique for extracting soil permittivity characteristics, the proposed approach is expected to provide accurate topsoil thickness estimation.

1.4. Hypothesis

The propagation of electromagnetic waves across media is assumed to be useful for detecting the boundaries between soil layers and estimating topsoil thickness [16]. The dielectric properties and wave reflections at the interfaces of different soil layers can be utilized to determine topsoil thickness [17]. Mathematical models that link electromagnetic wave parameters with soil characteristics can be developed to accurately estimate topsoil thickness [18][19].

The SFCW radar system offers sufficient spatial resolution for soil thickness estimation [20]. The bandwidth required for an SFCW radar system depends on the desired spatial resolution and the specific characteristics of the soil. Due to its flexibility in frequency range settings, the SFCW radar system provides a strong rationale for its selection in this research [21].

The SFCW radar system is also capable of simultaneously estimating the soil's dielectric properties along with soil thickness [22]. The dielectric property information, derived from the reflected electromagnetic signals, can be used to enhance the accuracy of soil thickness estimation [23]. Furthermore, both the estimated soil thickness and dielectric property data can be converted into the time domain for further analysis [24][25].

1.5. Research Limitation

The scope of this study is limited to the development of a method for estimating topsoil thickness using SFCW radar. The experiments are conducted at both laboratory and field scales. The laboratory-scale testing is performed on a soil prototype placed in a box measuring 224 × 122 × 61 cm. The detection process focuses solely on the topsoil layer; thus, the reflection coefficients of deeper soil layers and beyond are not considered in this study.

1.6. Research Methodology

This study employs a quantitative experimental approach designed to develop and evaluate a method for estimating topsoil thickness using Stepped Frequency Continuous Wave (SFCW) radar technology. This approach is chosen due to its ability to produce accurate and reliable quantitative data for measuring soil layer thickness non-destructively and rapidly. The proposed method in this study consists of two main components: the method for estimating soil permittivity values and the method for detecting soil layer boundaries. These two methods are combined to effectively estimate the thickness of the topsoil layer. The SFCW radar system is used because of its flexibility in radar modeling and its capability for preliminary system studies on specific applications, making it well-suited for prototyping the topsoil thickness estimation method.

The research framework includes three primary stages: numerical simulation, laboratory testing, and field testing. Numerical simulations are conducted to model and understand the behavior of radar wave propagation in soil media with varying parameters such as permittivity, conductivity, and topsoil thickness. These simulations aim to provide initial predictions and assist in designing effective experiments. Laboratory testing is designed using a soil medium contained in a box equipped with an aluminium plate as a bottom reflector to generate strong, clear, and stable reflected signals. This approach allows controlled validation of the method and ensures accurate estimation of the topsoil thickness. Aluminium is selected as the reflector due to its max conductivity and excellent electromagnetic reflective properties. Field testing is conducted at a tea plantation location at PPTK Gamboeng to evaluate the method's effectiveness under real conditions, including the influence of weed presence and surface unevenness. Data collection in the field is performed using linear scanning at fixed intervals, enabling systematic and representative data acquisition. The stages undertaken in this study include:

- Determining the method for detecting boundary layers in a layered medium, projected onto the soil layer case.
- Establishing the method for estimating soil permittivity to support thickness determination based on boundary detection.

- Designing laboratory experiments and modeling the SFCW radar system.
- Conducting experiments for data acquisition, processing, and analysis, focusing on identifying radar wave reflection peaks to estimate topsoil thickness.

Data collected from these three stages are processed and analyzed using time-domain and frequency-domain signal processing techniques to identify radar wave reflection peaks that mark soil layer boundaries. Validation of estimation results is performed by comparing radar data with reference measurements from laboratory tests and manual field measurements.

1.7. Research Methods

This research is conducted through a series of systematic stages to develop and evaluate a method for estimating the thickness of the topsoil layer using Stepped Frequency Continuous Wave (SFCW) radar technology.

1. Literature Review

In the initial stage, an in-depth literature review is performed regarding topsoil and its environmental impact. Data related to soil characteristics and the overall soil layers are studied, including key factors such as electrical properties, thickness ranges, and other attributes that play crucial roles in assessing soil quality. Additionally, existing techniques and methods for measuring topsoil thickness are explored, including relevant applications of Ground Penetrating Radar (GPR) and the principles of electromagnetic wave propagation in layered media. The preparation of a State-of-the-Art (SOTA) review aims to access up-to-date technological and methodological information to serve as the theoretical foundation for this study.

2. Theoretical Model Development and Simulation

This stage involves the formulation of theoretical and numerical models based on the literature review and the design of experimental methods to be implemented. Numerical simulations using MATLAB are conducted to model radar wave propagation in soil media with varying parameters such as permittivity, conductivity, and topsoil thickness. These simulations aim to evaluate the influence of these variables on radar signal behavior and the accuracy of thickness estimation.

3. Experimental Study Modeling

After completing the theoretical and numerical modeling, the next step is to design the laboratory experimental model. The experiment is conducted using a soil container of specific dimensions equipped with an aluminium plate as the bottom reflector to generate strong and stable reflection signals. The SFCW radar is mounted on a tripod at a height of 30 cm above the soil surface, transmitting stepped frequency waves ranging from 100 kHz to 6 GHz. Reflection signals are recorded point by point with a 2 cm interval, producing A-scan data that are then compiled into B-scan images.

4. Experiment Implementation and Data Acquisition

In this phase, the experiment for data acquisition, processing, and analysis is conducted based on the designed model. Radar wave reflections from soil layers are analyzed by detecting peak signals obtained from reconstructed data processed using MATLAB. The distance between these peaks is then used to estimate the topsoil thickness by converting results from the frequency domain (FFT) into length units such as centimeters or meters.

5. Field Testing

To evaluate the method's performance under real-world conditions, measurements are carried out at a tea plantation site with varying surface conditions, both clear and covered by weeds. Field data are collected using a linear scanning method with a 2 cm interval and processed following the same procedures used in laboratory experiments.

6. Accuracy Evaluation and Report Preparation

The estimated thickness results are compared with actual reference data from both laboratory tests and manual field measurements to assess the accuracy and reliability of the developed method. Finally, all stages of the research are compiled into a thesis report following the prescribed academic format.

1.8. Thesis Contribution

This research is expected to contribute to technological innovation by introducing the use of SFCW radar for estimating topsoil thickness, enhancing the understanding of the influence of soil permittivity values, and facilitating more effective plantation management. The findings of this study may also serve as a foundation for further research in the fields of soil monitoring and radar-based technologies.