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Ground-Penetrating Radar (GPR) for subsurface root-zone and soil-layer imaging in Kaluwara (Diospyros Ebenum) forests of Sri Lanka

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Abstract
Kaluwara (Diospyros ebenum) commonly called Ceylon ebony is a culturally and economically important hardwood species in Sri Lanka. Its conservation has been increasingly challenged by soil degradation, root decay and a long history of selective and illegal extraction. Traditional forestry methods provide limited subsurface information and are often invasive, making them unsuitable for rare-wood habitats. This study introduces Ground-Penetrating Radar as a non-destructive tool for imaging subsurface conditions in Kaluwara forests. Initial observations from a set of early GPR survey lines are presented together with a comparison of existing assessment methods. The preliminary results indicate that GPR can detect major roots, decayed zones, buried stumps, and soil-layer boundaries in dry-zone soils. As this work represents the first phase of a broader preservation project further field-based data collection is needed to validate and refine these findings.

Keywords: Kaluwara, diospyros ebenum, ground-penetrating radar, subsurface imaging, dielectric constant, root detection, soil layers, Sri Lanka’s forest conservation, non-destructive assessment

Introduction

Kaluwara is one of the most distinctive hardwood species in Sri Lanka’s dry-zone landscapes, and its ecological role has shaped both forest structure and cultural heritage. Understanding the condition of this species begins with recognizing its biological and environmental characteristics.

Fig 1: Diospyros ebenum (Kaluwara), commonly known as Ceylon ebony.

The species is characterized by its dense, dark hardwood and slow growth habit, occurring primarily in Sri Lanka’s dry-zone and intermediate-zone forests. Its ecological and cultural significance, combined with historical overharvesting and habitat fragmentation, makes it a priority species for conservation and non-destructive assessment methods such as GPR.

1. Background

Kaluwara (Diospyros ebenum) is one of the Sri Lanka’s most valued hardwood species. Kaluwara wood been used for centuries in traditional craftsmanship, temple architecture and high-value furniture for there dark noble appearance. The slow growing and habitat specific to dry-zone and intermediate-zone environments makes it more vulnerable to over harvesting. Habitat distribution making it further rare. Studies on Sri Lankan dry-zone forests highlight the ecological sensitivity of these habitats and the pressures placed on native hardwood species as (Wijesundara 1, Seneviratne and Gunatilleke 45) explained.

2. Historical Decline and Damage to Kaluwara in Sri Lanka

Kaluwara has been severely depleted throughout the history of Sri Lanka due to cultural pressure, economic necessity, and environmental factors. During the pre-colonial and colonial periods, the species was selectively cut for its prized timber, without necessarily replanting. The species' slow rate of growth meant that it could not regenerate fast enough to meet the rate of extraction. The colonial period further exacerbated the pressure on indigenous forests due to plantation agriculture and timber extraction, resulting in the clearance of dry zone forests (Schmerbeck and Naudiyal 176).

After independence rapid development, population growth and land-use further reduced Kaluwara habitats. Urban expansion, agricultural encroachment and infrastructure projects further contributed to the degradation of remaining. Illegal logging became a major threat due to the high market value of Kaluwara timber, which is widely recognized for its hardness and commercial appeal (SriHerbs). The removal of mature seed-bearing trees weakened the species’ long-term regenerative capacity.

Environmental stress has compounded these pressures. Soil erosion, declining soil fertility and prolonged dry seasons affected Kaluwara’s growth and stability. In some areas, trees show signs of root decay, soil compaction, and reduced structural support. These conditions are difficult to assess using traditional forestry methods. Today, Kaluwara is considered a vulnerable and heavily depleted species, and its fragmented distribution and history of overexploitation highlight the need for modern, non-destructive assessment tools that can support conservation and restoration.

3. Limitations of Existing Assessment Methods

Traditional forestry techniques provide useful information but cannot reveal subsurface root architecture or soil anomalies without causing disturbance. Soil pits and trenching are accurate but destructive. Auger sampling is limited to soil texture and cannot detect roots. Visual Tree Assessment focuses only on above-ground symptoms. Increment coring and resistograph drilling are invasive and unsuitable for protected species. Electrical Resistivity Tomography is non-destructive but offers low resolution for roots. Remote sensing is effective for canopy monitoring but cannot detect subsurface features (Lillesand *et al*. 2015) [6]. These limitations show the need for a non-destructive method capable of imaging subsurface conditions.

4. Introducing GPR to Rare-Wood Forestry

Ground-Penetrating Radar is a non-invasive technique that can image roots, soil layers, and buried anomalies. It is widely used in archaeology, engineering, and environmental studies, and its theoretical foundations are well established in near-surface geophysics (Daniels 12; Jol 45; Hugenschmidt 1121). Although no published studies have applied GPR to Diospyros ebenum or other rare-wood species in Sri Lanka, GPR has been widely used to detect tree root systems in forestry research (Butnor *et al*. 1269; Stokes *et al*. 49; Guo *et al*. 1). This study explores how GPR can be used to assess subsurface conditions in Kaluwara forests.

5. Objective

The objective of this study is to present initial observations and demonstrate how GPR can detect subsurface features relevant to Kaluwara conservation, including major lateral roots, decayed or hollow root zones, buried stumps, soil-layer boundaries, and lateritic hardpan layers.

Study Area

The study was carried out in a dry-zone forest region in Sri Lanka where remaining populations of Kaluwara are scattered but still accessible for fieldwork. Dry-zone forests in Sri Lanka are shaped by long seasonal droughts.

High surface hardness and a mosaic of mixed vegetation that consists of both native hardwoods and secondary growth. The landscape has been impacted by historical selective logging and general forest degradation patterns as documented in regional ecological studies (Wijesundara 1; Seneviratne and Gunatilleke 45).

The soil types in the region of interest are more consist of red-brown earth and lateritic horizons. The soil types are also known to have varying capacities for moisture retention and the presence of compacted horizons, which affect root growth and the reflectivity of the subsurface. Hardpans and iron nodules are common in dry-zone soil profiles and can cause high contrasts in dielectric properties, which influence radar penetration and clarity. The dry season also enhances surface hardness and the reduction of near-surface moisture, which tends to improve GPR signal penetration relative to tropical soils.

Vegetation in the region is characterized by a mix of dry zone species including mature Kaluwara trees, shrub vegetation and regrowing forests. Selective logging in the past is evident in the form of disturbed soil patches, canopy irregularities, and occasional stump remains. Such environmental factors influence the radar response and offer a practical scenario for assessing the performance of GPR in Kaluwara environments.

Methods

1. GPR Equipment and Settings

A commercially available Ground-Penetrating Radar system with a 400 MHz antenna was used for the initial field surveys. This frequency was selected because it offers a practical balance between depth penetration and the resolution needed to detect root-scale features in dry-zone soils. In similar near-surface applications, 400 MHz antennas have been shown to provide clear imaging of subsurface structures while maintaining workable penetration depths (Daniels 12; Jol 45). Key acquisition settings included a time window of 60 to 80 nanoseconds, a trace interval of 2 to 5 centimeters, and a combination of automatic and manual gain adjustments. All surveys were conducted as single-line transects to preserve the raw character of the early-phase data.

2. Soil Dielectric Properties and Velocity Assumptions

Depth estimates were based on dielectric values reported for red-brown earth and lateritic soils in Sri Lanka. Dry red-brown earth typically has a dielectric constant between 6 and 12, while lateritic layers may reach values between 12 and 20 depending on moisture content. These values correspond to radar wave velocities of roughly 0.09 to 0.12 meters per nanosecond. Because this study represents an early phase of field exploration depth calculations relied on these published values rather than on hyperbola fitting. This approach is common in preliminary GPR work where the goal is to establish baseline interpretive patterns before detailed calibration (Hugenschmidt 1121).

3. Survey Layout

Five short survey lines were established around mature Kaluwara trees and in adjacent forest areas. Surface debris was cleared to ensure consistent antenna contact and to reduce interference from loose vegetation or stones. The layout was designed to capture variation in root distribution, soil conditions, and disturbance patterns within a compact study area.

4. Data Processing

Processing was intentionally minimal to preserve the natural character of the early radar signatures. The steps included background removal, time-zero correction, and gain adjustment. Filtering was kept to a minimum so that the reflections could be interpreted without the influence of heavy processing. This approach aligns with recommendations for early-phase ecological GPR studies, where maintaining the integrity of raw signals helps establish a reliable interpretive framework (Daniels 12).

5. Interpretation Framework

Subsurface features were interpreted using categories commonly applied in forestry-related GPR research. Strong hyperbolas were taken to represent major roots, while weaker or asymmetric hyperbolas were interpreted as smaller or partially decayed roots. Diffuse reflection zones were associated with disturbed or moisture-rich soil, and continuous reflectors were linked to compacted layers such as lateritic hardpans. These interpretive categories are consistent with patterns documented in previous studies on root detection using GPR (Butnor *et al*. 1269; Stokes *et al*. 49; Guo *et al*. 1).

6. Clutter Sources

Several natural features in dry-zone forests can generate clutter or obscure weaker reflections. These include stones and lateritic nodules, termite mounds, dense surface root mats, and pockets of soil moisture. Such features can produce secondary reflections or mask the signatures of smaller roots. Recognizing these clutter sources is essential for interpreting radargrams in complex forest environments.

7. Hyperbola Geometry

Hyperbolic signatures were interpreted using standard GPR geometry. The apex of each hyperbola corresponds to the shallowest point of the object, and the curvature reflects the contrast between the object and the surrounding soil. This geometric relationship is a foundational principle in GPR interpretation and is widely used in both environmental and archaeological applications (Jol 45).

Results

The early GPR transects revealed several consistent subsurface patterns that correspond to root structures, disturbance zones, and soil-layer boundaries. These patterns appeared clearly even with minimal processing and provided a reliable foundation for interpreting how radar signals behave in Kaluwara forest soils.

1. Initial Observations

The first set of radargrams produced clear and interpretable reflections that showed how roots, soil layers, and disturbed zones appear beneath Kaluwara forest floors. The contrast between major structural features and background noise was strong enough to allow confident interpretation. These early signatures form a baseline for understanding radar behavior in dry red-brown earth, a soil type commonly associated with mature Diospyros ebenum.

2. Patterns Observed Across Survey Lines

Across the five survey lines, several recurring reflection types emerged. Strong and symmetrical hyperbolas were recorded near mature trees, indicating the presence of large lateral roots. In contrast, weaker and more irregular hyperbolas appeared in areas where field observations suggested partial decay or reduced root vitality. Some transects displayed broad and chaotic reflection zones that aligned with patches of historical logging activity, likely representing compacted soil, mixed debris, or remnants of removed stumps. Other profiles showed clean horizontal layering typical of undisturbed red-brown earth, reflecting stable soil horizons with minimal disturbance.

Table 1: Ground-Penetrating Radar (GPR) survey lines collected around mature Diospyros ebenum trees in a dry-zone forest of Sri Lanka

Survey line	Depth Range(m)	Observed features	Interpretation	notes
Line 1	0-2.5	clear hyperbola at 0.85-0.95m	Major lateral root	Strong amplitude. Dry soil improved clarity
Line 2	0-3.0	weak hyperbolas at 0.4-1.1m	small roots	Slight signal loss due to moisture patch
Line 3	0-2.0	diffuse, chaotic reflections	disturbed soil or possible decay	area known for past logging activity
Line 4	0-3.0	strong reflector at 1.05m	buried stump	Sharp boundary. Likely old felling site
Line 5	0-2.5	clean, horizontal layering	undisturbed soil	Good penetration. Minimal vegetation interference

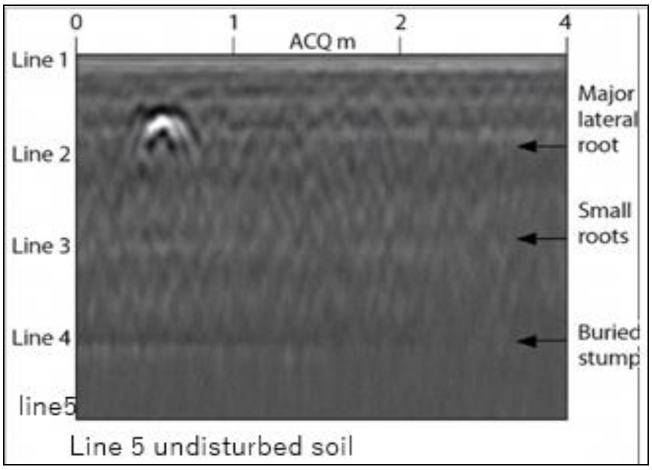

Fig 2: Composite radargram segments from all survey lines, illustrating the range of subsurface features detected during this phase.

The radargrams show strong hyperbolas associated with major lateral roots, weaker asymmetric hyperbolas linked to smaller or partially decayed roots, diffuse reflection zones corresponding to disturbed soil from past logging activity, and clean horizontal layering typical of undisturbed red-brown earth. These early signatures illustrate how GPR responds to subsurface structures in Kaluwara forest floors and form the baseline for subsequent phases of the study.

A composite figure is used here because each survey line revealed a different type of subsurface feature that could not be captured in a single radargram. The segment labeled Line 1 shows the strong and symmetrical hyperbola that marks a major lateral root. Line 2 presents the weaker hyperbolas that correspond to small roots. Line 3 highlights the diffuse and irregular reflections that indicate disturbed or decayed soil. Line 4 shows the sharp reflector produced by a buried stump. Line 5 displays the clean horizontal layering of undisturbed red-brown earth. Together these segments provide a compact visual summary of the main reflection patterns observed across the study area and help establish the interpretive framework used in this early phase of the research.

The initial evaluation of GPR has successfully demonstrated that it works as a non-destructive method for studying Kaluwara root systems and subsurface conditions. Because the results are promising, the Kaluwara conservation project can confidently move forward to broader, field-based research in the next phase.

Discussion

1. Value of GPR for Kaluwara Conservation

Previous results from this research suggests that Ground-Penetrating Radar is suitable of offering useful subsurface data in Kaluwara habitats without damaging sensitive forest floors. The capacity to trace large lateral roots, outline regions of partial decomposition, and differentiate buried stumps from regions of whole soil layers is clearly a useful function for conservation efforts. Such data may be used to inform the early diagnosis of structural weakness in mature trees, inform tree stability assessments, and trace regions where soil compaction or past logging activity may impact regeneration. As a slow-growing species with limited natural recruitment, the use of non-destructive methods that can trace hidden subsurface conditions may inform Kaluwara management and restoration.

2. Limitations

Several limitations emerged during this early phase of fieldwork. Clay-rich soils can reduce radar penetration, especially during wetter periods when dielectric values seems to increase. Variations in soil moisture may also distort reflections and bring difficulties to distinguish between roots and other subsurface features. Another fact is dense vegetation and uneven terrain can restrict antenna movement physically and limit the placement of survey lines. Another operational limitation is such that interpretation of radargrams requires trained personnel who can recognize the difference between true subsurface features and clutter produced by stones, termite mounds, or surface root mats. These limitations highlight the need for continued field testing and calibration to refine the interpretive framework for Kaluwara forests.

Future Work

Future stages of this research will expand the scope of field surveys to include a wider range of Kaluwara forest sites across the dry zone. It should be noted that broader sampling will help determine how soil variability, moisture conditions, and forest disturbance influence radar responses. Integrating GPS-based mapping will allow the spatial distribution of roots, stumps, and soil layers to be visualized more clearly and compared across different forest patches.

A limited program of ground-truthing will be carried out where feasible to refine depth estimates and improve confidence in the interpretation of hyperbolic signatures. Additional antenna frequencies must also be tested to evaluate how different resolutions and penetration depths perform in red-brown earth and lateritic soils. These steps will support the development of a subsurface risk-assessment model that can guide conservation planning, restoration efforts, and long-term monitoring of Kaluwara populations.

Conclusion

This early-phase study shows that Ground-Penetrating Radar can serve as a practical non-destructive tool for examining subsurface conditions in Kaluwara forests. The initial observations demonstrate that GPR can reveal major lateral roots, zones of partial decay, buried stumps, and soil-layer boundaries in dry-zone red-brown earth. These findings highlight the value of radar imaging for understanding the hidden structure of Kaluwara habitats, especially in areas affected by historical logging or soil disturbance.

The results also show that meaningful subsurface information could be obtained with minimal processing. That is important factor for field applications in remote or sensitive environments. While the interpretations presented here are preliminary, they provide a foundation for more detailed surveys and calibration work. By continuing field-based data collection and expanded sampling across multiple forest sites and testing of additional antenna frequencies will help refine the interpretive framework and support the development of a non-destructive monitoring approach for the conservation of Sri Lanka's rare hardwood species.

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