ISERME 2024 Proceedings
2nd September 2024 – Sapporo, Japan
https://doi.org/10.31705/ISERME.2024.26

Spatio-Temporal Analysis with Machine Learning for Sustainable Management of Abandoned Quarries

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Abstract

The abandoned quarries demand not only appropriate rehabilitation but also continuous monitoring. If these sites are left unmanaged, they can create significant environmental and ecological impact due to changes in land-use and land-cover. Monitoring of abandoned quarries are often overlooked due to challenges such as accessibility, safety and costs involved. Hence, there hardly exists a systematic monitoring approach or appropriate guidelines for managing quarry sites upon termination of the extraction activities. Thereby the presence of hazardous environments will be unavoidable with a substantial resistance on the quarry industry for not so sustainable closure procedures and following up actions. To overcome these challenges, sufficient monitoring of quarry sites and surroundings to enforce appropriate rehabilitation strategies with post monitoring that has minimal on-site involvements would be essential. For such purposes, analysing remotely sensed data would be applicable, based on the quality of data collection, processing and sufficient ground truthing. Accordingly, this study aims to develop an automated classification approach for mapping the land cover in the regions of abandoned quarries. It employs a comprehensive methodology that includes data preparation, feature extraction and selection, hyperparameter optimization, and identification of the algorithm that exhibits better accuracy. The efficacy of machine learning models - decision tree (DT), random forest (RF), and support vector machine (SVM) - were critical to analyse Landsat 8 and Sentinel 2 satellite images at selected sites in Anuradhapura, Sri Lanka. The outcome reveals that the SVM model produced the highest accuracy of 91.30% with a kappa index of 0.898. This superior performance of Sentinel 2 images could be attributed to their higher spatial resolution compared to Landsat 8 and SVM's efficient handling of high-dimensional data. Furthermore, SVM's robustness against overfitting using regularization, and its flexibility in dealing with complex separations through kernel functions would have facilitated the computations in addition to textural features and spectral indices incorporated to augment the model training procedure. It was also evident that augmenting the number of features can help alleviate the misclassifications that occur when exclusive use of spectral data. Utilizing the developed machine learning algorithms, a temporal analysis was performed on land cover from 2018 to 2022 to obtain a comprehensive overview on the changes. This analysis underscores the potential for monitoring land cover changes in abandoned quarries for effective management and rehabilitation strategies with minimal human intervention.

Keywords: Adaptive monitoring; Land cover; Image analysis; Support vector machine

1. Introduction

The extraction of valuable minerals and rocks from earth is essential to provide materials for infrastructure, construction, and numerous industrial processes required for modern lifestyles. Quarrying is one such activity that poses a range of environmental and socio-economic challenges, provided appropriate rehabilitation activities does not happen. The extensive excavation, rock blasting, and transportation involved in quarrying can result in landscape alterations, biodiversity loss, and safety hazards [1]. Adverse effects of these activities underscore the pressing need for effective strategies to responsibly monitor and manage abandoned quarries. Distinctive capabilities of remote sensing and image processing to access locations that are otherwise hard to reach with reduced manual work saving both labor and time, has made substantial contributions for the spatial monitoring, including adaptive management of abandoned quarries.

Efficiently delineating the existence of abandoned quarry sites and their spatial extent using satellite or unpiloted aerial vehicle (UAV)-based imagery, classified by traditional methods are common on previous studies [2]. These conventional approaches are restricted by their reliance on the assumption of normal pixel distribution, susceptibility to outliers and sensitivity to variations in illumination conditions [3]. In general, existing studies that employ satellite or UAV imagery for similar activities provide valuable insights at the spatial level. However, their reliance on traditional algorithms often limits their accuracy, especially when dealing with complex spatio-temporal patterns and subtle spectral variations. [4]. Hence, a comprehensive examination on the efficacy of machine learning (ML)-based pixel-level classification to assess the long-term monitoring of abandoned quarry sites, seems a necessity. Such ML-based approach is particularly important to ensure replicability and transferability of algorithms to similar scenarios and temporal monitoring [5].

Accordingly, this study introduces a comprehensive pixel-level ML-based classification to monitor the spatial and temporal proximity dynamics of abandoned quarries using satellite images. The outcomes of this study shall establish a robust workflow considering spatial and temporal aspects with suitability evaluations. This workflow is designed to enable informed decision-making, with a systematic and adoptive approach for the sustainable and responsible management of abandoned quarries.

2. Methodology

The study was conducted on selected abandoned quarry site in Anuradhapura District of Sri Lanka, which has numerous abandoned quarries left as open craters upon ceasing operations. These abandoned quarries pose significant environmental, social, and economic challenges to the contemporary community and its diverse land cover in the neighborhood. A region spanning 500 m from the boundary of the selected quarry site was delineated for land cover characterization to generate unique classes representing distinct type of land cover found within the area. The land cover was categorized into seven distinct classes as agriculture, water, rock exposure, barren land, algae bloom area, building, and forest. Images from Landsat 8 with a spatial resolution of 30 m, and Sentinel 2 with a finer spatial resolution of 10 m, captured during identical time periods in March 2021, were used for the study.

2.1 Optimal Pairing of Satellite Images and Machine Learning Algorithms

Landsat 8 and Sentinel 2 images were corrected for atmospheric and radiation errors to mitigate variations imposed by illumination and external factors. Specifically, the blue, green, red, and near-infrared bands were selected from both types of images to facilitate appropriate characterization. Selection of these four bands were sufficient for the process with a balance between accuracy efficiency while reducing the computational demand for the ML-based classification.

Ground truthing for the selected seven classes and respective spectral features were subject to machine learning based classification. Decision Tree (DT), Random Forest (RF), and Support Vector Machine (SVM) algorithms were used for this purpose. The hyperparameters of these algorithms, which have a significant impact on classification accuracy, were adjusted to achieve optimal performance. In the DT algorithm, tree depth, samples per node, and random seed were adjusted; in the RF algorithm, the tree depth, samples per node, and forest size were modified; and in the SVM, the kernel type, cost, gamma, and degree were changed. These adjustments were made to identify the optimal set of hyperparameters for each individual algorithm and dataset. The study reports the classification accuracy based on the algorithms with these optimized hyperparameters.

The ML models were subject to a rigorous evaluation process using five-fold cross-validation. This process involved splitting the dataset into five subsets and training and validating the models five times, with each time a different subset reserved for validation. Based on this comprehensive assessment, the overall accuracy of the models was determined. Further, per-class accuracy was assessed using confusion matrix. The algorithm that demonstrated the highest overall accuracy was considered to be the optimal choice under given circumstances. The same with its optimum hyperparameters, and the best-performing features extracted from specific satellite data, was employed for temporal analysis.

2.2 Temporal analysis

To enhance the classification accuracy of the temporal dataset, the best-performing algorithm identified according to Section 2.1 was subjected to additional training. This training incorporated additional features extracted from 2018 satellite data that represents an entirely distinct agricultural season compared to the 2021 training set. The incorporation of additional spectral and textural features was further tested to enhance the accuracy of temporal classification. Specifically, the Normalized Difference Vegetation Index (NDVI) and Haralick textural features were integrated. This integration was intended to prevent model overfitting, which could occur due to a limited number of features. Classifications were conducted based on the developed model and satellite images of the selected study area from 2018 to 2022. Subsequently, the variations in land cover during the same period was also analyzed.

3. Results and Discussion

3.1 Outcomes of the Optimal Pairing of Satellite Images and Machine Learning Algorithms

A comparison of spectral feature-based classifications derived from Landsat 8 and Sentinel 2 data reveals that Sentinel 2 consistently outperforms Landsat 8, regardless of the classification algorithm used [Fig. 1]. This superior performance could be mainly attributed to the finer spatial resolution of Sentinel 2 images. Specifically, for the DT algorithm, Sentinel 2 imagery achieved its highest accuracy at 84.94% (Kappa Index: 0.82), while the best result for Landsat 8 was significantly lower at 67.85% (Kappa Index: 0.63). Similarly, for the RF algorithm, the peak accuracy with Sentinel 2 reached 83.85%, surpassing the top accuracy for Landsat 8, which was 64.28%. Furthermore, the SVM algorithm recorded the highest accuracy with Sentinel 2 at 91.30% (Kappa Index: 0.898), while Landsat 8’s maximum accuracy was 75% (Kappa Index: 0.708). These results clearly demonstrate the advantages of utilizing Sentinel 2 images for spectral feature-based classification.

SVM’s ability to efficiently handle high-dimensional data, prevent overfitting through regularization, and manage complex separations with kernel functions, outperforms rest of the ML algorithms used in this study on Sentinel 2 imagery. Further, the selected SVM model demonstrates a relatively consistent performance across all classes, with the per-class accuracy exceeding 78% for each of the seven classes.

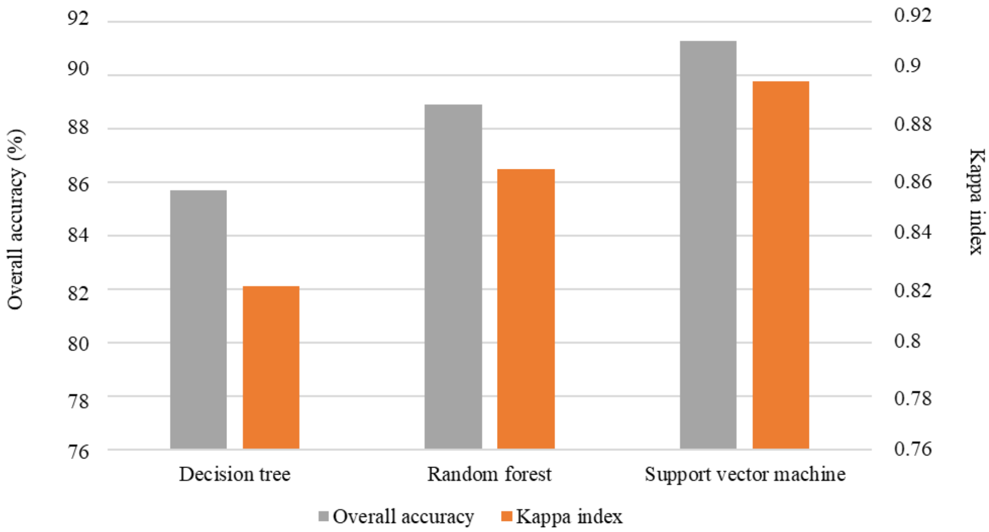

Figure 1 Overall accuracy and Kappa index of classification algorithms on Sentinel 2 data

3.2 Temporal analysis

To ensure the model's generalization, we incorporated data from a different season in 2018 into the training data set. This data was supplemented with a spectral index, NDVI, and eight Haralick textural features. Despite the consistent superior performance of the trained SVM model on identical datasets, its accuracy drops to 65.40% when applied to images from a different season. Augmenting the training data with a new feature set led to an improvement in accuracy on the different datasets, raising up to 80.90%. Analysis of the confusion matrix revealed that the model performed well across all classes, including the rare ones, thereby avoiding biased results. This demonstrates the effectiveness of our approach in enhancing the model's performance and generalizability.

The model's robustness and adaptability to temporal variations were evaluated with classification of a dataset from 2018 to 2022 related to an abandoned quarry site [Fig. 2]. It accurately applies to various time points, regardless of the season and demonstrates the effectiveness of the developed model.

Variations in the areas of seven distinct land cover types, observed over the period from 2018 to 2022 are illustrated from Fig. 3, reflecting substantial variations in the allocation among distinct land cover classifications. Expansion of agricultural land, from 1,023,375 m^2 in 2018 to 1,211,761 m^2 in 2022 highlights the conversion of alternative forms of land, such as barren lands, into agricultural purposes. Furthermore, the variability noted in algal blooms can infer the increased amounts of agricultural activities with potential links to the application of fertilizers. Release of excessive amounts of nutrients by fertilizers to adjacent water bodies could promote the growth of algae.

Considering these observations, it's crucial to apply this model cautiously when dealing with objects that are smaller than the spatial resolution of satellite images. Subsequent investigations may explore the classification at sub-pixel levels to address this constraint, or at object levels with the utilization of high-resolution images. Nonetheless, a similar workflow is applicable in such situations complimented by sufficient ground truthing.

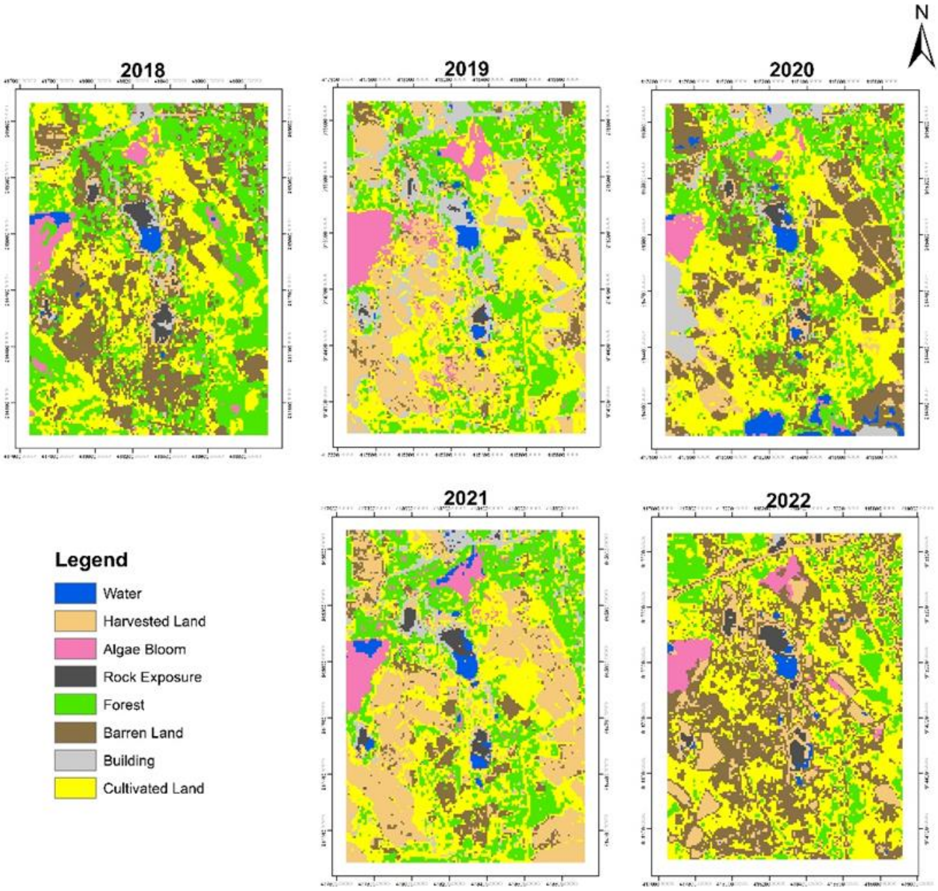

Figure 2 Classification of land cover surrounding the abandoned quarry for 2018 to 2022

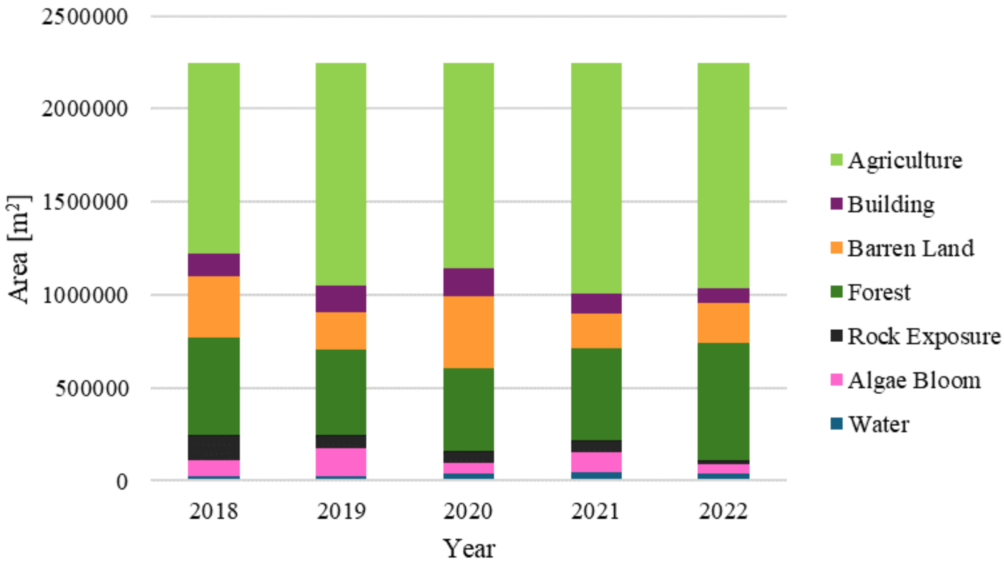

Figure 3 The variation land cover over the period of 2018 to 2022

3.3 Directives for rehabilitation of abandoned sites

Examination of the chosen abandoned quarry site through temporal analysis reveals the possibility of implementing suitable rehabilitation mechanisms with respect to the land use/land cover dynamics of the region. Thereby the recommendation of an inclusive approach for the site management can be achieved. The increasing trend in agricultural activities and forest cover identified for this area may demand a constructed wetland as one of the viable rehabilitation mechanisms. The depleting spatial extent indicated by the algal blooms and water bodies reinforces the above considering the water requirement for said activities. The capacity to draw such a conclusion underscores the potential of utilizing a ML-based classification approach for the adaptive management of similar abandoned sites. This method could be particularly useful in repurposing areas that have been left unused with challenging conditions for human access for preliminary investigations.

4. Conclusion

This study reveals the potential of utilizing machine learning algorithms for monitoring the changes in land cover over selected periods of times, neighboring abandoned quarries. The model enables continuous monitoring of the site with a mechanism that demands minimal human intervention and limited time. Such can help to develop adaptive management strategies to repurpose abandoned quarry sites with minimal environmental impacts and consumption of resources.

The ability to continuously monitoring the site remote allows early detection of environmental changes, enabling timely interventions to prevent adverse conditions and disturbances to the environment. This proactive approach is crucial for managing abandoned quarries, where ongoing surveillance can help ensure that rehabilitation efforts are effective and that the landscape is gradually restored to a more natural and sustainable state. Furthermore, by deploying an identical workflow with machine learning supported image analysis techniques, the authorities can maintain a detailed and up-to-date understanding of land cover dynamics over a particular region. This facilitates more informed decision-making and promotes sustainable development practices in the context of land use and resource utilization.

Accordingly, further studies are recommended to characterize high spatial and spectral resolution images along with textural features, as these have proven to increase accuracy in diverse and complicated conditions. In addition, sub-pixel level classification might also be considered to improve per-class accuracy when objects are too small to be captured due to the resolution of an image.

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