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Comparative analysis of unsupervised and deterministic satellite image segmentation methods for urban monitoring using machine learning

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Summary

This study focuses on comparing two image segmentation methods – unsupervised and deterministic (grid-based) – used to construct training datasets from Census data and Landsat imagery for machine learning algorithms in urban classification. The unsupervised method, Geographic Object-Based Image Analysis (GEOBIA), leverages the natural variability in urban textures to tailor pixel groups, potentially enhancing the contextual relevance of training data. In contrast, the deterministic method systematically segments imagery into uniform grids, prioritizing computational efficiency and scalability, ideal for extensive national-scale applications. By integrating the demographic richness of Census data with the spatial accuracy of Landsat imagery, this analysis explores how these segmentation techniques impact the predictive accuracy and efficiency of urban classification models. The results aim to guide national statistical offices in selecting the most effective segmentation strategy to optimize the use of geospatial and demographic data for updating urban cartography, ensuring robust and scalable machine learning models.

The document is presented to the Conference of European Statisticians' session on "Use of artificial intelligence and large language models in official statistics and authoritative geospatial data" for discussion."

I. Introduction

1. As urban areas continue to expand and evolve, the demand for timely and accurate urban data becomes more critical for sustainable development, resource management, and policymaking. Urban sprawl continues to shape the dynamics of landscapes and ecosystems, presenting significant challenges in urban planning and policy formulation. National Statistical Offices (NSOs) and geographical institutes are at the forefront of monitoring these changes to inform sustainable development and urban management.

2. Traditionally, precise tracking of urban sprawl has relied heavily on costly on-field operations or human-based photo interpretation of high-resolution satellite images. Both methods are not only expensive but also time-consuming, often lagging behind the rapid pace of urban development.

3. The integration of Census data and Landsat imagery through advanced image segmentation techniques offers a promising alternative. This paper compares two such techniques – unsupervised (Geographic Object-Based Image Analysis (GEOBIA)) and deterministic (grid-based) segmentation – used to create training datasets for machine learning algorithms in urban classification. By leveraging the detailed demographic data from the Census and the comprehensive spatial data from Landsat imagery, this study aims to assess the effectiveness of these methods in enhancing the efficiency, cost-effectiveness, and scalability of urban sprawl monitoring systems. This approach has the potential to transform the update of urban sprawl at the National Institute of Statistics and Geography (INEGI), enabling them to evaluate the classification results across productive areas and incorporate these insights into the cartographic updating process, thereby making urban monitoring more attuned and responsive to the evolving demands of urban development.

II. Methodology

A. Data acquisition and pre-processing

4. The study employed Landsat 8 multispectral imagery for two temporal snapshots, 2010 and 2020, covering the entire nation of Mexico. These images were acquired from the United States Geological Survey (USGS) Earth Explorer platform. Prior to segmentation, all images underwent a series of pre-processing steps including atmospheric correction using the Moderate Resolution Imaging Spectroradiometer (MODIS)/6S method, radiometric calibration to convert digital numbers to reflectance, and geometric correction to ensure alignment and accuracy of the spatial features.

B. Image segmentation methods

1. Unsupervised segmentation (GEOBIA)

- **Algorithm configuration**: The GEOBIA was implemented using the Remote Sensing and GIS Software Library (RSGISLib), an open-source remote sensing library. We configured the segmentation to minimize within-cluster variance and maximize between-cluster separation using a k-means clustering algorithm.

- **Feature extraction**: This step involved extracting spectral features along with textural features derived from the Grey Level Co-occurrence Matrix (GLCM) to enrich the classification context.

2. Grid-based segmentation

- **Grid setup**: The imagery was divided into uniform grids of 500m × 500m cells. Each cell was treated as a separate entity with no overlap, simplifying the computation and standardizing the input size for classification algorithms.

- **Feature aggregation**: For each grid cell, mean spectral values along with other statistical parameters such as standard deviation and median were calculated to represent the grid cell in the classification process.

C. Classification and performance evaluation

- **Machine learning framework**: Auto-Sklearn 2.0, an automated machine learning tool, was used to classify urban and non-urban areas. The framework was configured to automatically select the best algorithm and hyperparameters based on cross-validated performance.
- **Training and validation**: The classification model was trained on a labelled dataset derived from INEGI urban extent maps for the years corresponding to the imagery. A 70–30 split was used for training and validation sets, respectively.
- **Performance metrics**: Classification accuracy was primarily evaluated using the Macro-F1 score, along with other metrics such as precision, recall, and overall accuracy to provide a comprehensive assessment of the model’s performance.

D. Results

5. The comparative analysis of the unsupervised (GEOBIA) and grid-based image segmentation methods for urban classification using multispectral Landsat imagery revealed distinct performance metrics, which are critical in understanding their respective efficacies in handling large-scale geographic data.

6. Grid-Based Segmentation Performance:

- The grid-based segmentation method exhibited a remarkable Macro-F1 score of 97.68 per cent. This high score indicates a strong agreement between the predicted classifications and the true data, highlighting its robustness in standardizing large datasets efficiently.
- The superior performance of the grid-based method can be attributed to its systematic approach to handling spatial data, where the uniform grid structure likely reduced the complexity and variability seen in the raw satellite images, leading to more consistent and predictable classification outcomes.
- Efficiency Analysis: The method’s efficiency was also observed in its computational performance, where the simplicity of the grid structure allowed for faster processing times and lower computational resource consumption, making it particularly advantageous for national-scale applications that require regular updates and quick turnarounds.

7. GEOBIA Segmentation Performance:

- On the other hand, the GEOBIA method achieved a Macro-F1 score of 95.20 per cent, which, while slightly lower than the grid-based method, still reflects a high level of accuracy in urban classification tasks.
- This method’s performance is commendable given its more complex approach to segmenting images based on spectral similarities, which involves analysing the texture and other contextual information within the urban landscapes. Such detailed analysis is crucial for applications requiring a nuanced understanding of urban areas.
- The slightly lower performance in the GEOBIA method might also be linked to its sensitivity to heterogeneity in urban settings, where diverse building materials and non-uniform structures can introduce variability that challenges the segmentation algorithm.

8. Comparative Analysis:

- The comparison between the two methods suggests that while GEOBIA offers depth and detail, making it suitable for applications that benefit from a granular analysis of urban features, the grid-based method provides a more streamlined and efficient approach that may be preferable for broader, large-scale monitoring and updating of urban classifications.

- The choice between these methods should therefore consider the specific requirements of the project, including the scale of application, the need for detail, and the available computational resources.

9. Implications for Cartographic Updating and Urban Planning:

- These results have significant implications for National Statistical Offices and Geographical Institutes engaged in cartographic updating and urban planning. The efficiency and accuracy of the grid-based method make it an excellent candidate for integrating new data into national geospatial databases and for conducting regular monitoring of urban expansion or changes.
- Conversely, the detailed classifications provided by the GEOBIA method can be instrumental in urban planning and development projects that require detailed analysis of the urban fabric to guide decision-making processes related to zoning, infrastructure development, and environmental impact assessments.

III. Discussion

A. Importance of efficient methods for national scale applications

10. Efficient segmentation methods are critical for NSOs tasked with monitoring and planning urban development across extensive geographic areas. The following points illustrate the importance of these methods:

- **Scalability and timeliness**: Efficient methods like grid-based segmentation can process large volumes of satellite data quickly, making it feasible to monitor urban expansion in real-time across entire countries.
- **Cost-effectiveness**: Reducing the computational resources and time required for data processing directly decreases the costs associated with urban mapping projects.
- **Consistency and standardization**: Standardized methods facilitate consistent urban data collection, which is crucial for comparing urban development trends and making informed policy decisions.

B. Applications for national statistical offices

- **Urban expansion monitoring**: Implementing efficient segmentation methods allows NSOs to continuously track urban sprawl and analyse growth patterns, which is vital for urban planning and infrastructure development.
- **Resource allocation**: Reliable urban classification maps inform the equitable distribution of public services and infrastructure, ensuring resources are allocated where most needed.
- **Census planning**: Enhanced urban maps support the planning and execution of census activities, particularly in rapidly growing urban regions.

IV. Conclusion

11. Efficient image segmentation methods are essential for NSOs to manage urban data effectively at a national scale. This study’s comparison of unsupervised (GEOBIA) and deterministic (grid-based) segmentation methods demonstrates that while both provide valuable data, the grid-based approach, with its higher Macro-F1 score of 97.68 per cent compared to GEOBIA’s 95.20 per cent, offers a superior balance of efficiency, accuracy, and ease of use, making it particularly suitable for large-scale applications. The grid-based

method enables quicker data processing and simpler computational demands, facilitating timely updates to urban classifications essential for responsive urban management and policymaking. Although the GEOBIA method offers detailed urban textures beneficial for in-depth planning and environmental assessments, its relatively lower efficiency suggests it is best used selectively for projects requiring high-detail analysis. The findings recommend that NSOs adopt the grid-based approach for broad-scale monitoring while reserving GEOBIA for specific projects where detail is paramount, suggesting further research to enhance efficiency and explore hybrid models that combine the strengths of both segmentation methods.